ERGONOMICS

HUMAN FACTORS IN WORK, MACHINE CONTROL AND EQUIPMENT DESIGN

A Taylor and Francis International Journal

The Official Publication of the Ergonomics Research Society

Volume 1 **Number 1**

November 1957

ALERE FLAMMAM.
Printed and Published by
TAYLOR & FRANCIS LTD.
RED LION COURT, FLEET STREET, LONDON, E.C.4

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Price £1 5s. 0d. per part

Subscription price per volume £4 15s. 0d. post free, payable in advance

Agents for U.S.A. and Canada

Academic Press Inc., 111 Fifth Avenue, New York 3, N.Y., U.S.A.

$3.50 per part. $13.30 per volume.

EDITORIAL

The term 'Ergonomics' is derived from two Greek words and means literally 'the customs, habits or laws of work'. It was coined to denote an approach to the problems of human work and control operations which came into prominence during the second world war in relation to equipment for the fighting services, and which since the war has been widely recognized as having important implications for industry. The development of radar and of high-speed aircraft, the elaboration of operation-plotting rooms and of controls for ships and the designs of clothing for extremes of temperature, all emphasized that technical developments had reached a stage at which the capacities of the user rather than the potentialities of his equipment were setting limits to the performance of men and machines working together. For progress to be made, it was therefore necessary, that these human limits should be studied and given due consideration.

The study required the application of knowledge from the human biological sciences, especially anatomy, physiology and experimental psychology. Applications of these disciplines to practical problems had of course been made for a long time and had resulted in a number of important and classical reports. The wartime and post-war research differed, however, from what had gone before in three points of emphasis. Firstly it aimed at designing equipment to ensure that its operation was within the limits of human capacity, instead of trying to match men to the demands of tasks by selection and training. Secondly, the fact was recognized that the applied problems should be tackled in terms of fundamental principles. Thirdly, the essential unity between functional anatomy, physiology and experimental psychology became very clear, and the need was emphasized for close and sustained cooperation between workers in all three disciplines, and between these and physical scientists and mathematicians.

The wartime research workers brought to their studies a broad theoretical background by use of which they were able to by-pass many *ad hoc* specific studies in favour of approaches having more general implications. There were also important effects on the disciplines concerned: attention was called to a range of problems of basic theoretical interest which had hitherto lain unrecognized, and many of the problems upon which fundamental research had in the past been concentrated were seen in better perspective. There thus developed a two-way traffic between the research worker and those in the Services who had to design equipment and make administrative decisions about its use, and this has continued with the subsequent studies in industry.

Many examples could be quoted of research within this general area upon both physical and mental work. The determination of averages and ranges of body sizes, length of reach, and the force that can be applied by limbs, has affected the design of chairs, of seating in vehicles, and of work spaces. Important extensions have been made to previous studies on the measuring of physical load and the effects of climatic stress. Clear principles have emerged regarding the optimum design of instrument dials and scales and of controls for aircraft and machine tools. More recently there have been

important developments in the understanding of man as a communication channel transmitting and storing information and these seem likely to have a profound bearing upon the design of ' automation ' equipment.

Both research workers and industry have been aware of difficulties on the one hand, of making research understandable to ' users ' and on the other, of bringing field problems to the attention of those interested in studying them. Apart from differences of language and terminology, the accounts of research are scattered widely through scientific journals and unpublished reports which are not readily available to industry, or indeed to those outside the research workers' own disciplines. Further, a long process of laboratory research and preliminary field trials usually has to come between the birth of an idea which has practical importance and its application, which means that communication needs to take place in two stages : the passing of knowledge to industry must be preceded by exchanges of information between research workers. The Ergonomics Research Society was founded in 1949 with the object of providing those engaged in research of this kind with a forum in which members of different disciplines could meet and have the opportunity of discussion with interested persons in industry. Since then interest in ergonomics has expanded rapidly in many countries, resulting in a substantial membership of the Society outside Britain and the founding of groups having similar aims in Germany and the United States. Further important developments in Europe are likely in the relatively near future.

The present journal is therefore designed to further three types of communication : between disciplines, between research and industry, and between different countries. It will be an interdisciplinary scientific periodical for the exchange of research information ; at the same time it will provide those whose main interest is in practical applications with some articles of direct use and a larger number which give insight into likely future developments. The international board of editors will welcome contributions from any country in either English, French or German, and there will be summaries of the main papers in all three languages. It is hoped that the journal will thus appeal to those with a research interest in the human biological disciplines and also to engineering and machine-tool designers, industrial medical officers, and technical and managerial staff in industry. Although not dealing with routine work study or personnel selection, material will be included and techniques described which are likely to provide additional 'tools' for departments dealing with these procedures.

It is planned to publish nine main classes of material.

(1) Original research reports. These will inevitably be somewhat technical in presentation but it must be recognized that they are the essential means of advance in the field. They will doubtless be of primary interest to other research workers.

(2) Review articles. Some of these will be surveys of previous literature leading up to the definition of problems for future research or to indications for application. Others will give leading research workers who have made a series of contributions in a particular field the opportunity to survey and appraise their own findings reported in more detail elsewhere.

(3) Accounts of actual applications which have been carried out in a manner which permits the drawing of reasonably definite conclusions or which seem to have a significance beyond the actual case concerned.

(4) Discussions of theoretical issues of importance to research falling within the field of ergonomics. These will again be mainly of interest to other research workers.

(5) Descriptions of new apparatus and methods applicable to the study of ergonomic problems.

(6) Discussions of research needs by those in industry or elsewhere who are responsible for the design or use of equipment.

(7) Accounts of the work and organization of departments or units dealing with problems in the field of ergonomics.

(8) Letters to the editor containing brief notes on work in progress, comments or statements on topics of current interest in the ergonomic field. These need not preclude a fuller statement at a later date.

(9) Abstracts of articles in other journals and of unpublished reports which are available on request. Authors are invited to submit these to the editor for publication.

The journal will be the official organ of the Ergonomics Research Society and will publish the proceedings of the Society and other matters of interest to the Society's members. It should be emphasized, however, that contributions which reach the required standard will be accepted irrespective of whether or not their authors are members of the Society.

HUMAN LIMITATIONS AND VEHICLE DESIGN*

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This paper contains a review of research on road vehicle design in relation to human physiological, anthropometric and psychological factors

An important factor influencing efficiency in the operation of vehicles is the extent to which the automotive equipment has been designed to meet human capabilities and limitations. If instruments and controls are considered as extensions of the driver's sense organs, nervous system and body appendages, it is reasonable to expect that machines should be designed from the man outward. Mechanical design should be intimately related to the biological and psychological characteristics of the driver. If this point of view—usually referred to as human engineering, biotechnology, or engineering psychology—is carried out in practice, greater operational efficiency and fewer errors should result. Also, extensive redesigning of equipment after it is put into use should be eliminated (McFarland 1954, Chapanis *et al.* 1949).

An attempt should be made, therefore, to set forth the basic physical, physiological and psychological characteristics of the drivers. When such facts are studied in relation to the vehicle under given environmental conditions and at specific times and places, operational efficiency and safety can be improved in subsequent models of such equipment. Significant information of this type can be discovered chiefly by carefully controlled experimental studies and by operational analyses.

§ 1. Methods of Evaluating Human Factors in Vehicle Design

During the past eight years an extensive project has been carried out at the Harvard School of Public Health on human variables in the design and operation of vehicular equipment. The chief objective has been to improve operational efficiency and safety through the elimination of errors which result when design is not intimately related to the physical and psychological characteristics of drivers (McFarland and Moseley 1954, McFarland *et al.* 1955).

One of the initial steps in this project was to develop a manual of procedure for evaluating the extent to which human capabilities and limitations had been considered in the original design of such equipment (McFarland *et al.* 1953). The manual provided an outline for accumulating specific data on a large number of items in each major area of design having implications for the operator, as follows :

(1) Design of the seat, and layout of the working space for ease and efficiency of operation, including allowances for variations in human body size.

(2) Design and arrangement of visual displays to provide information for operating under normal and emergency conditions.

(3) Design of controls and their arrangement.

* This study is sponsored by the Commission on Accidental Trauma of the Armed Forces Epidemiological Board, Dept. of Defense, and supported in part since 1951 by funds from the Office of the Surgeon General, Dept. of the Army, U.S.A.

(4) Control of factors in the environment, including noise, vibration, temperature and toxic agents.

(5) Protecting the operator in the event of sudden deceleration.

1.1. *A Study of the Size Range of Professional Drivers*

In order to evaluate vehicles in regard to human body size, it is necessary to measure not only the dimensions of the vehicles but also the body sizes of the operators. The measurements of the human body necessary for establishing the dimensions of the working space and locating controls are as follows: (*a*) The maximum arm reaches attainable without altering the position of the body. (*b*) The extensions of these reaches which can be attained by the movement of the trunk or body. (*c*) The eye level of the man in the operating position. (*d*) Body dimensions in the operating position, that is, sitting heights, fore and aft and lateral measurements at various levels. (*e*) The leg reaches attainable without altering or disrupting posture (King 1948, Floyd and Welford 1953).

A great deal of human sizing data has been obtained for pilots in connection with cockpit design, but little specific information is available on driver populations (Morant 1948, Hertzberg *et al.* 1954). To acquire these data an anthropometric team from our staff conducted surveys in the field. Thirty-two measurements were taken on 100 bus drivers, 100 New England truck drivers, 70 Texas truck drivers, and 100 champion truck drivers competing in a National 'Roadeo' of driving skill.

The data are *not* presented in terms of averages, for the use of average values may account for many defects in vehicle design. The mean should not be employed directly, since, by definition the interior arrangements would be suitable for only 50 per cent of the operators in a normally distributed group. Provision for 90 or 95 per cent, or any other predetermined proportion of potential operators, will require identifying the correct cut-off points. For example, where arm reach for the operation of controls is under consideration, the cut-off point should be well below the average reach. In other situations, due consideration must also be given to the 50 per cent of the drivers whose dimensions exceed the average values as well as to the 50 per cent whose measurements are below the average (McFarland *et al.* 1953, Damon and McFarland 1956, McFarland *et al.* 1956).

In Table 1 the percentile distributions are given of three body dimensions, anterior arm reach, knee height, and sitting eye level height. These are known to be important in regard to the location of the seat and controls in vehicular equipment.

The problem of integrating anthropometric data with the static dimensions of cabs is one of varying complexity. The reason for this is that anthropometric data are obtained under static conditions. On the other hand, if a man is driving he is in a dynamic situation. As a result the static data cannot always be applied without additional study through the use of mock-ups in connection with subjects representing known points in the distribution of body measurements. Morant has stressed the importance of the dynamic point of view in anthropometric study.

Table 1

Percentile Distributions of Anterior Arm Reach, Knee Height, and Sitting Eye Height for Professional Bus and Truck Drivers

Percentiles	Anterior arm reach Inches	Knee height Inches	Sitting eye level height Inches
5	32·95	20·08	27·72
10	33·46	20·43	28·11
15	33·94	20·63	28·39
20	34·33	20·83	28·58
25	34·65	20·98	28·74
30	34·88	21·18	28·98
35	35·12	21·30	29·13
40	35·32	21·42	29·29
45	35·51	21·58	29·45
50	35·75	21·69	29·61
55	35·94	21·81	29·72
60	36·14	21·93	29·88
65	36·38	22·05	30·00
70	36·58	22·16	30·16
75	36·85	22·24	30·43
80	37·13	22·36	30·55
85	37·44	22·56	30·75
90	37·87	22·84	30·98
95	38·42	23·50	31·61
	Number : 312 Range : 30·66–41·67 Median : 35·75	Number : 301 Range : 19·29–25·98 Median : 21·69	Number : 309 Range : 26·38–32·68 Median : 29·61

Similarly, faulty design may be overlooked without direct observation of the driver operating his equipment. For example, when one truck model was evaluated, it was discovered that taller drivers could not operate the foot brake when the gear lever was in either of the two left positions (see Fig. 1). It was impossible for a tall driver to put his foot on the brake pedal without first shifting gears. For 80 per cent of the drivers the distance between the brake pedal and the bottom of the steering wheel was too short to permit the leg to move high enough to put the foot on the pedal. Furthermore, the gear-shift in either of the left positions was too close to the wheel to allow the leg to slip between. As a result, the foot was trapped on the floor until the driver could shift gears.

1.2. *An Evaluation Study of Trucks and Buses*

Using the procedures outlined in the manual described above, precise measurements were taken of a series of trucks and buses by a research team with training in engineering, industrial psychology, and operational analysis. The vehicles which were evaluated consisted of 13 trucks and 9 buses, all recent models, (McFarland *et al.* 1953). Several examples are given below of design faults revelead by these methods.

(1) Marked variations were found to occur in the overall working space provided for the drivers of trucks and tractors. In one instance, it was estimated that only the drivers representing the smallest 40 per cent of the group could be accommodated. However, if the manufacturer had given consideration to the driver, rather than solely to cab weight, this would not have been the case.

(2) Many errors were observed in regard to human sizing. In several models, for example, only 5 per cent of the drivers could comfortably reach and operate the hand brake. In others, only 60 per cent could be accommodated for knee height between the pedals and the steering wheel. Many of the taller drivers are unable to adjust their sitting position to obtain maximum visibility with regard to their instruments and the road ahead.

Figure 1. With the gear shift in the left position, the foot brake cannot be operated by most of the driver population.

(3) Failure to provide for adequate seat adjustment to allow for variations in human size was frequently reported by the drivers interviewed and from the objective studies of working areas. Probably the most striking defect was that the front of the seat could not be lowered for shorter individuals to enable them to operate the pedals without excessive pressure behind the knees. Some of the medical problems frequently observed in truck drivers are believed to be related to poor seat design and to failure to provide adequate shock absorbers.

(4) There was no standardization of shift patterns in the various models studied. This predisposes the driver to error in the event that he is transferred from one model to another. Many errors in selecting the correct gear have

been observed during normal runs. The location of the shift levers was not standard, with the exception that they were all for right-handed operators.

(5) Adequate vision from the cab was a serious problem while operating in residential and business areas. This contention is supported by an analysis of 57 light truck accidents involving fatalities which indicate that 50 per cent of the cases involved pedestrians. When operating during bad weather, the range of forward vision was reduced approximately 50 per cent, and visibility from the side was even less because of no provision for cleaning or defogging. Although the areas of the side windows were approximately the same, there were marked variations in the ability to see pedestrians on the right because of the distance of the driver from the right-hand window.

(6) Many errors have been observed in the location and design of electrical switches, especially for headlamps, fog lamps, and marker lights. In two models, the dimmer switch was found to be located directly beneath the foot pedals, close to the steering post (see Fig. 2). Thus, the driver may inadvertently operate the air horn or fog lights while attempting to dim his headlamps. Even if operated correctly, complex motions and longer reaction times are required to avoid the pedals. Since many accidents occur when approaching another vehicle, the location of the switch underneath the pedals may cause undue delay in pedal operation.

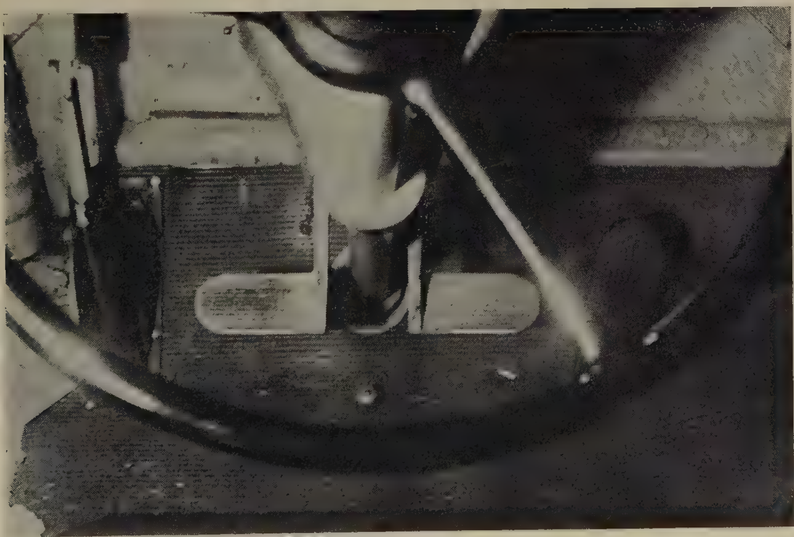

Figure 2. The foot-operated dimmer switch is located underneath the clutch and brake pedals, and close to the steering post.

(7) More attention should be given to the location of instruments on the panel with respect to ease of visibility. For example, in many cases, the air gauge was placed directly behind the steering wheel and could not be seen by the driver without twisting his body out of a good driving position. Another instance is that of the r.p.m. indicator which was placed on the end of the dashboard away from the operator, so that it was virtually impossible to read it accurately.

(8) In the studies of carbon monoxide concentrations in trucks and tractors, the maximum safe levels were exceeded in almost every instance when the sample was taken after 15 minutes in a closed cab with the engine idling. On repeated tests with one tractor, the level was high enough to be lethal in one hour. However, in no instance during road operations was an unsafe level of carbon monoxide found. The maximum operational measure was 0·0025 per cent, which is a safe level.

It has been possible to influence the manufacturers to introduce certain changes in design. Follow-up evaluations have been made on 1956 models to determine the extent to which our recommendations have been incorporated in the newer vehicles (McFarland *et al.* 1957).

1.3. *An Experimental Approach to the Design of the Driver's Compartment*

The principle that static dimensions require supplementation by techniques involving the dynamic setting of the driver at his task was applied in an additional experiment. The objective was to determine the ranges of adjustability in the seating and controls which would result in optimal accommodations for individual operators, (Kephart and Dunlap 1955, McFarland 1956). A cab mock-up was devised, in which nine different adjustments could be made. This apparatus is shown in Figs. 3 and 4. Subjects representing the 5th, 50th, and 95th percentiles of Army drivers ‘ drove ’ the device in a simulated driving task at various settings of the adjustments. The inter-relationship between the various items in the cab were determined by statistical analysis, and recommendations were made for their location and ranges of adjustability. A significant finding of the experiment was that when the settings were those at which the ‘ driver ’ was most ‘ comfortable ’ in the apparatus, fewer errors were made on the ‘ driving ’ task.

§ 2. Operational Studies of Driver Activities

A careful job analysis often forms the basis for planning improved designs and practices. This can be done at various stages at which the following may serve as an example :

Table 2

Advance Analysis of Equipment

I. Operational job analysis :	1. Requirements of task.
	2. Working area.
	3. Characteristics of displays and controls.
II. Blueprint phase :	1. Prediction of efficiency.
	2. Human limitations.
	3. Anticipation of errors.
III. Mock-up stage :	1. Performance of duties.
	2. Physical size of operators.
	3. Skill requirements.
	4. Age of operators.
	5. Accessory equipment.
	6. Interfering structures.
	7. Physiological stress.
	8. Errors or near accidents.

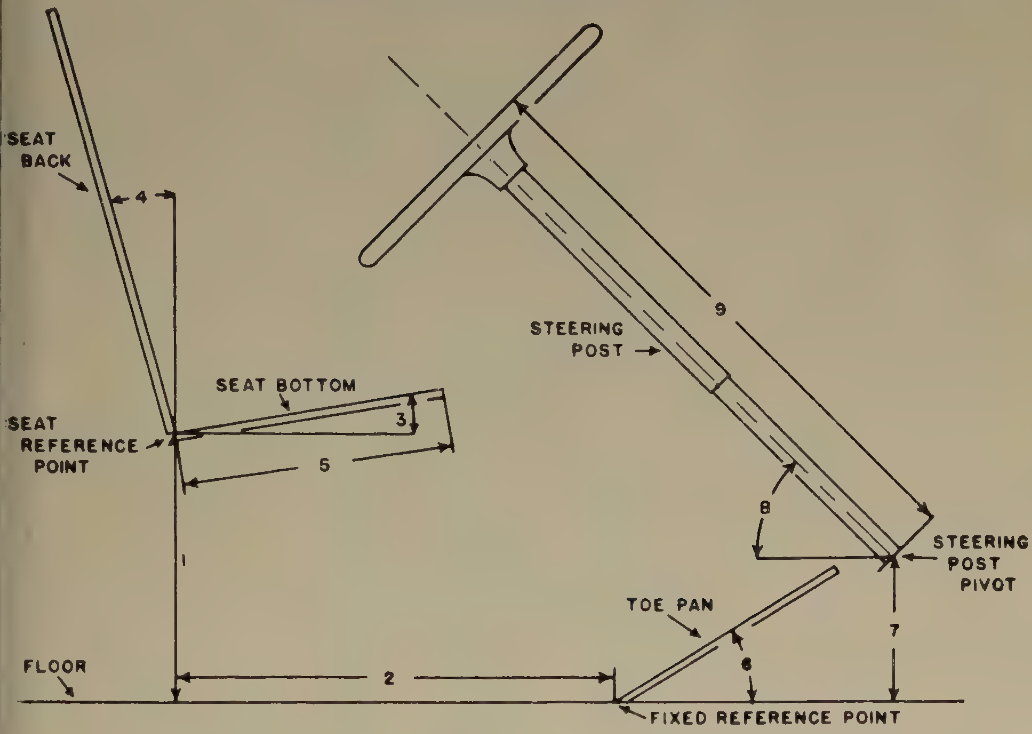

Figure 3. Schematic diagram of the mock-up truck cab. The figure shows the various adjustments available to the subject and the manner in which each was measured.

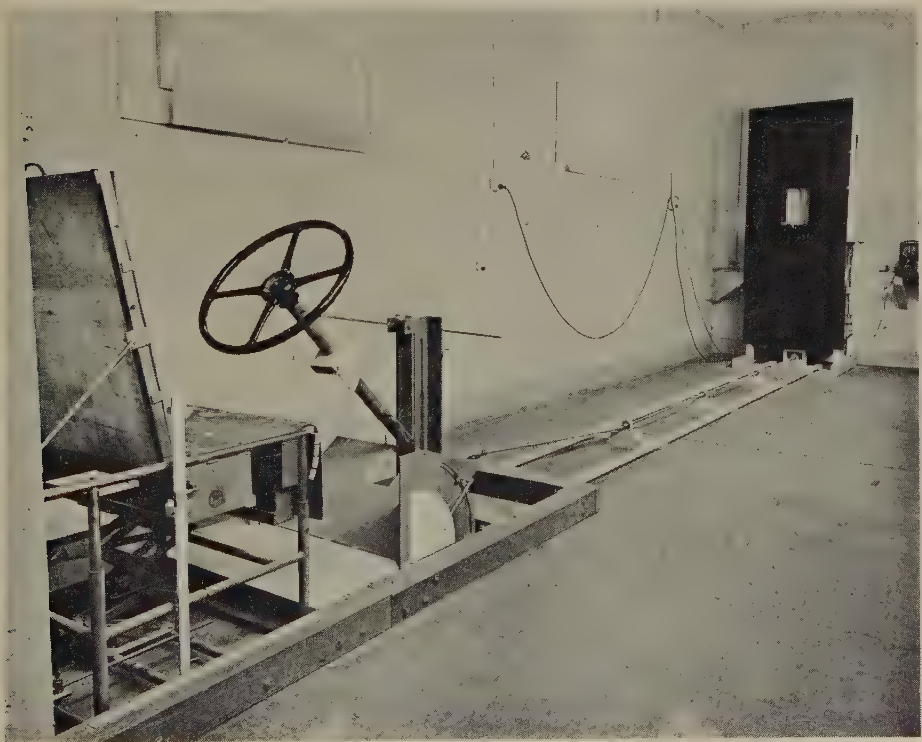

Figure 4. The mock-up cab, and the layout for the simulated driving task.

Once this analysis is made, equipment can be standardized. Then the worker will be able to react quickly and accurately in moments of stress or uncertainty and to devote his entire attention to critical situations which may arise. Finally, errors can be revealed by an evaluation of the working procedures and arrangement of equipment. This may be done (1) by interviewing operating and supervisory personnel ; (2) by observing performance under real or simulated conditions, including the time and frequency of operations, motion picture and sound recordings, and equipment-rating devices ; and (3) by analysis of critical incidents. In this way, the inter-relationships or links between the equipment and workers can be appraised in arriving at a final evaluation for safe and efficient operating conditions (McFarland 1956).

While not directly related to the immediate problem of linking design faults to errors, it is relevant to mention the long-term effects of design failure on the men who have to live with them for a number of years. Excessive vibration may result in renal difficulties, and noise in partial loss of hearing. Moreover, poorly designed seats cause spinal ailments. Good drivers will be forced into new occupations long before they should retire (McFarland *et al.* 1954). New and inexperienced men must be trained as replacements, thus increasing the possibility of accidents through the lack of experience which comes only with years of operating over the highway (McFarland 1953).

2.1. *An Analysis of the Activities and Distribution of Work Load of Bus Drivers*

The objective of this study was to observe the simultaneous actions of the operator's hands, feet, and eyes while driving a vehicle, and to determine not only the peak loads on each part of the body but also to study the important components of each task. The method involved photographic and interval sampling of the head, body, hand, and foot movements in turning, decelerating, accelerating, shifting, and braking. The data were obtained by trained observers on our staff while riding with several drivers and noting the frequency and time of each activity. Instances of driver errors were also noted. This information was used to describe the requirements of the job, the proportion of time spent in different activities, and the number of errors made by each operator. Unusually complicated activities were photographed with an electrically operated 16 mm motion-picture camera which permitted exposure of film at the rate of two frames per second.

Trips were made between Boston and New York, as well as in Texas and the far west, during both day and night operations. Observations on the Boston–New York route were recorded during seven of the nine and one-half hours required for each trip ; the route involved both city traffic and open highway conditions over varying terrain. The frequency distributions were based on approximately 1500 observations for the vehicles, and 1500 for each part of the body mentioned above (see Table 3). They indicate that the bus was operating in the straightaway position 74 per cent of the time, and that the driver had his eyes to the front 78 per cent of the time. The left hand was kept almost continuously on the wheel (99 per cent), while the activity of the right hand was divided between the wheel (81 per cent) and the gear shift (11 per cent). The right foot was on the accelerator 87 per cent of the time and on the brake 13 per cent of the time (McFarland and Moseley 1954).

Table 3

The Frequency of Observed Items and the Percentage of Time that Each Occurred

Vehicle	Frequency	Per cent
Straightaway	1243	73·7
Right turn	94	5·6
Left turn	86	5·1
Stopped in traffic	154	9·1
Passing	58	3·4
Pick-up	37	2·2
Discharge	14	0·8
	1686	99·9

Right Hand	Frequency	Per cent
Wheel	1200	80·9
Shift	161	10·8
Rest	97	6·5
Hand brake	4	0·3
Instruments	6	0·4
Fares	3	0·2
Signals	0	0·0
Horn	13	0·9
Waving	0	0·0
	1484	100·0

Eyes	Frequency	Per cent
Front	1153	78·0
Right front	68	4·5
Left front	81	5·4
Right	21	1·4
Left	23	1·5
Left mirror	95	6·4
Right mirror	25	1·7
Instruments	8	0·5
Down	9	0·6
	1483	100·0

Left Hand	Frequency	Per cent
Wheel	1465	98·8
Rest	17	1·1
Hand brake	0	
Instruments	0	
Fares	0	
Signals	0	
Horn	0	
Waving	2	0·1
	1484	100·0

Right Foot	Frequency	Per cent
Accelerator	1286	87·0
Brake	198	13·0
Rest	0	
	1484	100·0

An analysis of the activities of the drivers of buses used in inter-city operations revealed that the automatic transmission makes possible a reduction of from 5 to 25 per cent in the total amount of activity per minute in a normal passenger run. The advantage in simplifying the driving operation is that it frees the driver from routine as much as possible so that he can react intelligently to other aspects of the driving situation and the care of passengers.

Micromotion studies of each activity showed the link value of various controls, the time necessary to do these activities, and the critical components of various tasks. The data collected on the methods of shifting, vision from the cab, and the use of switches and instruments were also of value in considering improvements in the design of equipment.

The various pedal relationships offer a promising area for study and improvement. In some instances the brake and accelerator pedals are so placed that they force the driver's foot to make lengthy movements in three directions before the brake can be activated, i.e. up, over and then down. In some designs this vertical distance approaches 9 in. and represents a substantial portion of a man's braking time. Sometimes the two pedals are

of identical design and material, making it almost impossible for the driver to distinguish between the pedals by 'feel' alone. Undoubtedly this feature has been responsible for many critical situations and probably a certain proportion of real accidents as well, especially with drivers new to the particular vehicle. Lack of standardization of the pedal locations and structure causes additional problems when switching from passenger vehicle to bus or truck.

The results may also be helpful in improving the design and location of various controls and switches in that the relative frequency of use is indicated. Individual muscle groups may become acutely fatigued from holding a steady position. The lower right leg and foot, for example, may react slowly in emergency situations, after maintaining steady continuous pressure against the accelerator pedal. In some situations, as on runs in mountainous country, continuous turning and shifting are required. Mechanized or hydraulic aids to steering will continue to reduce the possibility of errors during such combined manoeuvres.

2.2. *A Study of the Proficiency of Bus Drivers in Operating Their Equipment*

In evaluating the proficiency of individual drivers in handling their equipment and appraising their susceptibility to errors or accidents, direct observation was made of 30 bus drivers during scheduled runs in New England. The route was 23 miles long, and the time 55 minutes.

Detailed recordings of the driver's activities were made during each minute. A numerical score was assigned to 22 possible errors for each driver. It was found that the frequency and types of errors clearly differentiated between the good and poor drivers. The eleven kinds of errors of greatest value in this respect are shown in Table 4. Correlations of 0·71 and 0·61 were obtained between the 'error' score and (*a*) the safety director's rankings and (*b*) the operator's past accident records. Study of the detailed records indicate that these experienced drivers made few errors in the elementary skills of their task but made many more in the more complex aspects of manoeuvring. One possibility of reducing such errors is through improvement in the design of the equipment to simplify the more complicated operations (McFarland and Moseley 1954).

Table 4

The Discrimination Value of Types of Errors Observed in Bus Drivers

Type of Error	Discrimination value (X^2)
Follows vehicle too closely	5·6
Errors at stoplights and signs	3·8
In wrong lane of traffic for conditions	3·8
Writing on day card in motion	2·8
Improper passing	2·3
Improper turn	2·3
Excessive speed	2·3
Collecting equipment for relief in motion	2·3
Attention not on road	1·4
Errors at Intersection	1·1
Miscellaneous Inattentions	1·1

Figure 5. Goniometer in place to measure the areas of clear vision available from the eye position of the driver.

2.3. *A Study of the Eye-Movement of Drivers in Relation to the Location and Design of Instruments*

A study was made of the eye movements and fixations made by drivers. With a Bell-Howell A-7 Eyemo 35 mm camera eye movements were photographed as reflected in a mirror. The camera field also included a portion of the roadway ahead. Analysis of the films was in terms of (*a*) frequency of fixations, (*b*) duration of fixations, (*c*) point of fixation (e.g. instrument, mirror, forward field), and (*d*) link values. Sample findings from a bus run are as follows: viewing straight ahead, 87·6 per cent of the time; looking in left rear-vision mirror, 0·3 per cent of the time; looking in right mirror, 0·4 per cent of the time; viewing extreme right field, 1 per cent of the time, passenger mirror, 0·01 per cent of the time. Average fixation time for left mirror was 0·45 sec, for the right mirror 0·7 sec, and for the passenger mirror, 0·5 sec. Link values were equally strong for right and left mirrors. Few fixations were observed for dashboard instruments. The analysis may prove to be of interest not only in showing the marked differences in time required to obtain the necessary information from instruments, but the inter-relationships most important for efficiency of operation (Commission on Accidental Trauma, 1954–5, 1955–6).

2.4. *Analysis of Critical Incidents in Bus and Truck Operations*

A study was made of near accidents during 4000 miles of routine long-haul bus operations in the far west. The analysis revealed that as a rule critical situations develop very rapidly and are of short duration. Of the 66 *near accidents* observed, 53, or 80 per cent of them were closely related to the three most common types of accidents which actually occur on the highway, namely, side-swipe, rear end, and head-on collisions. The most important variables contributing to the critical situations were as follows: (1) following too closely; (2) following too closely while approaching to pass, i.e. cornering; (3) operator inattention, i.e. dozing at the wheel; (4) vehicle running off the road; (5) intersection errors; (6) errors in passing; (7) operating in wrong lane of traffic (8) leaving and entering the roadway; and (9) pedestrian errors (McFarland and Moseley 1954).

Very similar findings resulted when an observer obtained detailed descriptions of 48 near accidents which occurred during 20 long-haul truck trips totalling 5000 miles. Most of the incidents were precipitated through operational errors, or errors in judgement on the part of drivers. In the observations made both in trucks and buses, the outstanding characteristic was the speed with which critical incidents arise, and the very limited time available for carrying out emergency procedures. Even though the manoeuvres leading into a near accident may have consumed a half a minute or more, as when large vehicles overtake and pass at a low speed differential, the elapsed time of a near accident was of the order of a second or two, often less than one second. Critical situations with such limited time relations were most frequent when visibility of the roadway ahead was restricted, as at blind curves and intersections, at the crests of hills, and in fog. Under such circumstances, the limits of human reaction time and physical braking distance may be exceeded, and safety is dependent upon the design features which reduce perception and reaction time even fractionally, and reduce the time and effort of emergency manoeuvres in controlling heavy equipment (McFarland and Moseley 1954).

§ 3. Studies on Visibility and the Design of Windshields

The design of windshields, side windows, and rear vision mirrors represents one aspect of the visual display. Studies of operating efficiency and accidents indicate that additional research should be carried out in these areas. Adequate vision from the cab remains a serious problem in some models although marked improvements have been made in others.

3.1. *Man's Area of Vision in Relation to Windshield Design*

The range and field of view for drivers from all types of vehicles is an important area for human engineering research. In a study associated with the Harvard project, methods are being developed for the objective rating of vehicles of various kinds in terms of the visibility from the eye position of the driver. An instrument has been devised which permits numerical comparison of the outside physical area visible through various arrangements of windshields, windows, and supporting structures with the total area man is capable of viewing (see Fig. 5). This study is concerned with improving the design provisions for seeing other vehicles and stationary objects in time to introduce appropriate action (Commission on Accidental Trauma, 1954–5, 1955–6).

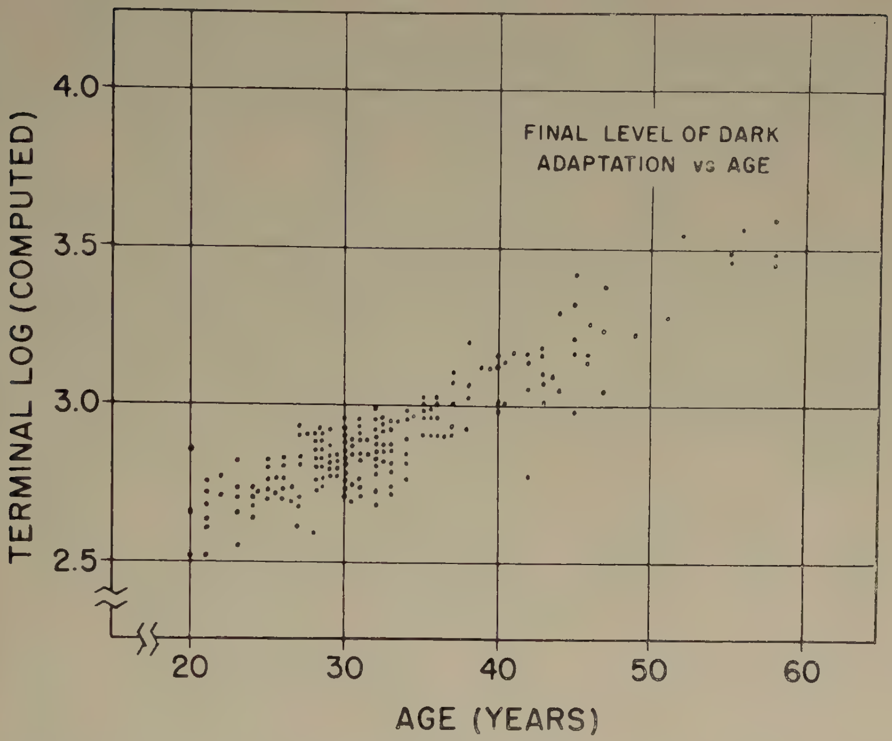

Figure 6. Scatter plot showing the relationship between age and the final level of dark adaptation.

3.2. *Visibility Through Tinted Windshields at Low Illumination*

An excellent example of the importance of the inter-relationships between the operator, his equipment, and the environment is afforded in the use of tinted windshields on vehicular equipment. These windshields have been widely accepted in America, and certain advantages may be obtained in reducing the glare from bright sunlight and aiding in the control of temperature within the car. Since the National Safety Council reports that accident rates are three times higher at night than in the daytime, this design feature deserves careful consideration in order to utilize the principle to the greatest advantage without introducing hazards.

The first step in our research project in this area involved the measurement of the percent of transmission of light with various types of tinted windshields currently in use. The absorption of light was from 25 to 30 per cent as compared to about 12 per cent for ordinary safety glass. The next step was to obtain dark adaptation curves and to test recovery from glare, with and without the tinted windshield. Tests were also made for visual acuity and depth perception. The results uniformly indicated a loss in visual efficiency resulting from the tinted glass. Objects just perceptible without the glass could not be perceived through the tinted windshield unless their brightness was increased by a factor of about 1·45. This differential obtained both for the fully dark adapted eye, and the eye adapted to a level of illumination prevailing while driving with headlights at night (Commission on Accidental Trauma 1954–5, 1955–6).

The factor of age is an important consideration in evaluating the practical significance of the above findings. An experiment was first carried out to determine the relation between age and the light sensitivity of the eye. Dark adaptation curves were obtained on 200 subjects varying in age from 20 to 70. A regular decrease in light sensitivity of the dark adapted eye occurred with age. The correlation was found to be 0·89, and it was observed that for every increase of 13 years in age, a doubling of the intensity of lights would be required for them to be just perceptible (McFarland and Fisher 1955). See Fig. 6.

A third phase combined the variables age, tinted glass, and a low level of illumination. The technique involved testing light sensitivity after a period of dark adaptation. The experimental conditions were as follows: (*a*) no optical filter, (*b*) clear windshield glass, and (*c*) tinted windshield glass. The results are shown in Table 5, and graphically in Fig. 7.

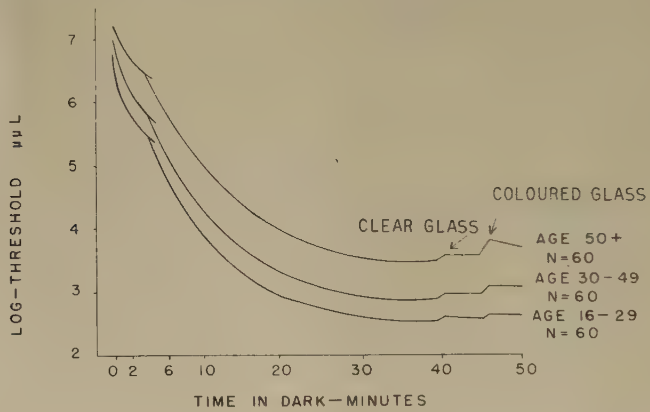

Figure 7. Dark adaptation in relation to age, and the effect of clear and tinted windshield glass on thresholds of sensitivity to light.

Table 5

Threshold Values (Log $\mu\mu$l) for Dark Adaptation as a Function of Age and Tinted Windshields after 40 minutes in dark

Subjects N	Age	Without filter	Difference	With clear glass	Difference	With tinted glass
60	16–29	2·518	0·017	2·535	0·145	2·670
60	30–49	2·861	0·045	2·906	0·162	3·068
60	50+	3·469	0·064	3·533	0·190	3·723

An inspection of the log differences in the above tables confirms the finding that even without the use of windshield glass, it is required that lights must be brighter to be seen by older persons than is the case with those of younger age. Our older subjects required an intensity of light at threshold levels nearly nine times as great as for the younger ones. While both clear windshield glass (88 per cent transmission) and tinted windshields (72 per cent transmission) have the effect of raising thresholds in dim light, the effect of the former is relatively slight. The effect of any filter is relatively more marked for the older person. The lights ' just seen ' through tinted glass by our older subjects were about eleven times brighter than those just perceptible to the youngest group.

The practical significance of these findings for vision at night through tinted windshields is being studied under operational conditions. This is important since previous experiments in this area have not adequately controlled such variables as age and foreknowledge of the location of objects to be perceived.

§ 4. Conclusion : The Advance Analysis of Equipment for Operational Efficiency and Safety

The point of view stressed in this paper is that the efficient and safe operation of motor vehicles is a function of the design of the equipment in relation to the characteristics of the operators. In general, it may be said that any control unnecessarily difficult to reach and operate, any instrument difficult to read, any seat inducing poor posture or discomfort, or any unnecessary obstruction to vision may contribute directly to operating errors on the part of the driver. In addition, the cumulative effects of such difficulties are sure to induce fatigue, resulting in the overall deterioration of driver efficiency and safety.

All possible faults in equipment and in the working area of a car, truck, or bus, as well as the capacities of the operator, should be subjected to an *advance analysis* for preventing errors and accidents. If defects are present, it is only a matter of time before some operator ‘ fails ’. Advance analysis assumes the following considerations. The first involves an operational job analysis that should include a survey of the nature of the task, the work surroundings, the location of controls and instruments, and the way the operator performs his duties. The second implies a *functional concept of errors*—that is, it anticipates the errors that may occur while the operator is working at the machine. The repetition or recurrence of near or real accidents clearly indicates a need for redesigning. A third consideration relates to *human limitations*. It should be assumed that no driver is a perfect one. In fact, he may be far below the ability adjudged by the designer. If his duties are too complex, the cumulative burden is great and he reaches or exceeds his limits of attention and ability. Finally, a wide *margin of safety* should be provided to eliminate any possible situation that places the operator near his maximum ability with regard to aptitude or effort, especially when adverse factors enter the picture (McFarland 1946).

Cet article contient une revue d'études sur la construction des voitures de route par rapport aux facteurs physiologiques, anthropometriques et psychologiques humains.

Der Aufsatz enthält eine Übersicht von Forschungsarbeiten über Strassenfahrzeugbauarten in bezug auf die menschenphysiologischen, anthropometrischen und psychologischen Faktoren.

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EFFECTS OF NOISES OF HIGH AND LOW FREQUENCY ON BEHAVIOUR

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Three groups of subjects worked for two sessions in noise at a five-choice serial reaction task. During one session the noise was restricted to frequencies above 2000 c.p.s., and during the other to frequencies below. The high frequency noise gave more errors in performance, although the difference was significant only at the highest intensity of 100 dB.

When reaction times were measured to the same noises, the first reaction of a series with the same type of stimulus was slower when the stimulus was low intensity and low frequency. With high frequency or high intensity stimuli this was not so.

It thus appears that sounds more likely to interfere with work also produce a faster reaction when themselves acting as signals, confirming a view already advanced about noise effects; that the effect is due to competition between various stimuli to control response.

§ 1. Introduction

Although noise is known to leave many human functions unaffected (Kryter 1950), it has recently been shown that work in high noise intensities may be affected: the same rate of work is maintained, but rather more mistakes are made (Broadbent 1953, 1954, Jerison 1954). The effect appears only on prolonged tasks requiring unremitting attention. There are two questions which immediately suggest themselves, and which the experiments described here are intended to answer. Firstly, how does the size of the effect vary with the frequency and intensity of the noise? Secondly, what is the nature of the effect—does the noise produce a *general lowering of efficiency* or does it act by *distracting attention* from the main task?

§ 2. Experiment I

The purpose of this experiment was to compare the effects of three intensities of noise each at high and low frequency.

The noise was reproduced from a continuous loop tape recorder and played back through distributed loud speakers to give a sound field flat over the subject's working area. A tape recording of actual machinery noise, having roughly equal energy per third-octave band from 100 to 5000 c.p.s., was copied onto fresh tapes through filters passing frequencies either above or below 2000 c.p.s. These tapes were then used to produce the high and low frequency noises respectively. The three levels of intensity corresponded to physical levels of the high frequency noise of 80, 90 and 100 dB. The low frequency noise was reproduced at a level of 3 dB more intense in each case, this being found to give approximately equal subjective loudness (see Appendix). Some extra details concerning the room and the equipment used are given by Broadbent (1954).

The apparatus for the main task consisted of a panel carrying five neon lights and five brass contacts. When a particular light was on, a particular

contact was to be touched with a stylus : as soon as this was done a different light came on. The subject was shown the task and told to keep on touching the indicated discs ‘ without making any mistakes ’. He thus fixed his own rate of work. Further details of the task are given by Broadbent (1953).

Each subject performed two runs of 25-min separated by a 24-hr interval. During one run the high frequency noise was played and during the other the low frequency noise, the order of presentation being rotated for alternate subjects. In the main experiment 24 subjects were used in three equal groups. Each group received one of the intensity levels specified above.

All subjects were Naval Ratings under the age of 30. All but four of them were Fleet Air Arm Ratings, mostly air mechanics ; the other four were a stoker, a steward and two seamen. Most subjects were thus used to working in loud noise in their normal employment, but not of course in the particular noises tested.

2.1. *Results*

Numbers of correct responses made in a given time showed no effects of noise—a result which agrees with previous work. The numbers of errors (touching a wrong contact) for the six main conditions are shown in Table 1. It will be seen that there was no difference between the effects of high and low frequency noise at 80 or 90 dB, the slight advantage for the low frequency being within chance limits. But at 100 dB the high frequency noise was substantially worse than the low, and the difference was shown to be significant (see Appendix).

Table 1

Mean Errors with Noise of Various Spectra and Intensities. The level of noise given is the intensity of the high frequency noise : the other noise was at equal loudness (= +3 dB physical intensity).

Frequency	Level of Noise		
	80	90	100
High	24	23	49
Low	22	22	32

It seemed possible at first sight that this result might have been due to the high frequency noise appearing louder so that the effect was not of pitch but of loudness. This interpretation is not likely to be true, because twelve of the subjects in fact regarded the low frequency noise as louder, while only nine so regarded the high frequency one. To be sure, however, an additional experiment was tried with two extra groups of 8 subjects each. Both groups received the low frequency noise at 103 dB as did the main group, but the high frequency noise was attenuated below the level of 100 dB used for the main group. With the first group it was attenuated by 4 dB and all subjects then regarded it as less loud than the low frequency noise. In the second group, a further attenuation of 4 dB was applied to the high-frequency noise, so that the low-frequency noise was even more markedly the louder. Nevertheless, in neither group did the subjectively louder noise produce more errors : in each case the errors were slightly, though insignificantly, greater in the high frequency noise. Loudness alone cannot therefore explain the difference between the two noises found in the main group.

A point not apparent in Table 1, but very noticeable in the statistical analysis and shown in Table 2, is that the subjects first meeting the task under the worst possible conditions do badly throughout the experiment. This has an important practical implication since it suggests that familiarity with a situation may determine whether or not there is an effect of noise spectrum. The result agrees with that of Jerison (1956) who reported an experiment on the effects of noise in which performance in quiet was apparently affected by earlier experiences of the same task in noise, and with some preliminary results by the writer from an experiment designed specifically to test this point. It is also in line with earlier work by Welford *et al.* (1950) who found that civilian aircrew who met an experimental task on return from flying performed it badly both then and later when rested, while those who met the task when they were fully rested did well both then and later after flying. The effect appears to be a general one.

Table 2

Mean Errors per Subject for those Performing in Noise of 100 dB Intensity. Note that the performance of those who received the high frequency noise on the first run was poor on both runs compared with the performance of the group whose first run was in low frequency noise.

	Subjects whose first run was with high frequency noise	Subjects whose first run was with low frequency noise
First Run	75	24
Second Run	32	24
Total	107	48

§ 3. Experiment II

The previous experiment shows that a high frequency high intensity noise has a more adverse effect on performance than a low frequency high intensity noise, but that the difference of frequency has no effect at low intensities. Now if the noise is a ' distractor ' which shifts the subject's attention to itself and away from other stimuli, we should expect these findings to be exactly reversed if the subject was asked to *react* to the noise rather than ignore it. If the noise produces a general lowering of efficiency, then response should be least efficient to a high frequency high intensity noise even when that noise is itself the stimulus to action.

Experiment II was therefore devised to measure reaction to the same noises used in Experiment I. It is generally accepted that increase of stimulus intensity will increase the probability and decrease the latency of reaction (Piéron 1952, Berlyne 1950), although the data for human reaction time indicate that increase of intensity ceases to be effective beyond certain range. The evidence on effects of frequency is however conflicting : Fessard and Kucharski (1935) indicate shorter latencies for reactions to high frequencies, while Chocholle (1940) found equal latencies. As we shall see, the results of Experiment II resolve this conflict.

The subject was seated with his back to a loudspeaker, 3 ft from his head. The speaker was connected through a change-over relay to the output of a tape recorder on which a tape of steady noise was running continuously. By

operating the relay the experimenter thus connected the speaker in place of a load resistance on the recorder, producing a sudden burst of noise from the speaker. Other contacts on the same relay started an electronic timer counting in 10 msec units. The timer was stopped by the subject pressing a key placed under his right thumb.

Each subject first matched the noises for loudness by a procedure described in the Appendix. Fifty reaction times were then obtained. Alternate groups of five reaction times used the high and the low frequency noise. At the end of each group the subject was informed that the other noise was about to be used, but was not given a demonstration of the stimulus. The experimenter said " Ready " 2 sec before each stimulus was given.

The interval between successive reactions was about 10 sec. At the close of the session another loudness balance was made as a precaution against consistent trends in balance. Half the subjects began with high frequency noise and half with low ; in each category half of the loudness balances were obtained with the high noise first and half with the opposite order.

Two groups were tested : Group I (14 subjects) at a level of 75 dB for the high frequency noise, and Group II (12 subjects) at a level of 100 dB. All subjects were again Naval Ratings under the age of 30 ; none had served as subjects in Experiment I.

Table 3

Mean Reaction Time in msec to Different Stimuli at Different Times after Change of Stimulus.

Stimulus		Position of Response in group of 5				
Intensity	Frequency	1	2	3	4	5
75	Low	209	199	187	196	189
75	High	196	198	193	187	187
100	Low	203	190	187	190	190
100	High	201	187	197	192	189

3.1. *Results*

Table 3 gives the mean reaction time for the first, second, third, fourth and fifth response in each group of five.

It is obvious from the table that there was little difference between the effects of the different kinds of signal at the end of the groups of five (i.e. when the particular signal was familiar). The beginning of the groups of five was a different matter. While it is true for all four signals that the first response took longer than the last, this was not statistically significant in the 100 dB group. In the 75 dB group, the high frequency noise showed a slight but not quite significant improvement from first to last response : but the low frequency noise gave a marked and highly significant improvement. The difference between low frequency and high frequency noise on the first response was quite insignificant in the 100 dB group, but easily significant in the 75 dB group.

Thus at low intensity the low frequency noise gave a slow response compared with the high frequency one : but the difference disappeared at high intensities. These results were exactly the opposite to those of Experiment I : it was even the case that the difference only appeared when the situation was relatively

unfamiliar whereas the effect of noise on visual work required a prolonged situation to show itself.

What of the conflicting results of previous workers? Chocholle (1940) who found no difference between the effects of different frequencies, used a large number of reactions under each stimulus condition and particularly comments on the need to familiarize the subjects with the stimulus. Fessard and Kucharski (1935) used small numbers of reactions, being concerned to avoid the effects of fatigue. They found that high-pitched tones gave shorter reaction times than low tones, but only at low intensities: at high intensities there was no difference. The present results, showing an effect which was substantial early in a series of stimuli but rapidly diminished, thus agree with both the previous papers and show that they are not really in disagreement.

It should be noted that preliminary experiments in the present research were carried out with pure tones rather than noises, and they gave very high variability with unfamiliar sounds. This variability masked any possible effect of pitch, and in general the results of this paper should not be assumed to apply to pure tones.

§ 4. Theoretical Discussion

There are two aspects of these results which are of theoretical interest: the fact that the noises giving least efficiency in Experiment I were not those giving least efficiency in Experiment II, and the particular nature of these noises. The first of these facts tends to confirm a ‘ distraction ’ view of noise, which has already been favoured by the writer for other reasons (Broadbent 1953). Such a view may be put formally by asserting that the perceptual system has a limited capacity, that there is therefore competition between information from different sensory channels to enter the system, and that the degree of success of a particular stimulus in this competition depends partly on its physical intensity and partly on the length of time which has elapsed since similar information succeeded in the competition. A loud noise will thus interfere with visual signals, particularly when the latter have been passing through the perceptual system for some time and have lost their novelty: but the noise itself, if it is given as a stimulus for action, will receive an efficient response, especially before it loses its novelty.

The second fact is that both high frequency and high intensity (above, say, 90 dB) seem to act in the same direction, increasing the likelihood of response. So far as intensity goes, it is perhaps not surprising that the more intense sound should have a higher priority since it is more likely to signal biologically important events. We may note also that post-stimulatory auditory fatigue increases sharply at a level between 90 and 100 dB (Hood 1950), presumably indicating the onset of sensory damage, and that Davis *et al.* (1955) have found that several circulatory variables, such as finger volume and pulse time, change considerably as the intensity of a sound stimulus is raised above 90 dB. Further, the sizes of the galvanic skin response, of muscle action potentials, and of respiration amplitude and cycle duration, increase disproportionately above 90 dB in their experiments. None of the recent experiments which have succeeded in demonstrating ill effects of noise has used a sound level of less than 90 dB.

§ 5. Practical Conclusions

Three broad suggestions emerge from these results.

Firstly, it is more urgent to reduce the intensity of irrelevant noise than that of noise which is an integral part of the work. This is because the effect of the noise is distracting rather than disabling, in contrast to some other types of adverse working conditions.

Secondly, it is probably more urgent to reduce high frequencies than low. Admittedly there are cases in these results in which frequency had no effect but when one sound was worse it was the high-frequency one.

Thirdly, the 90 dB level is a reasonable target figure below which noise should be reduced if possible. For reasons of comfort and understanding speech it may be desirable to reduce noise still further: but as yet no effect on efficiency has ever been proved with fainter noises.

This work owes much to the continual encouragement and advice of Dr. N. H. Mackworth and to the technical assistance of Dr. A. Carpenter and of members of Admiralty Research Laboratory. Thanks are due to the Royal Navy for supplying subjects and equipment.

Trois groupes de sujets travaillaient pendant deux séances dans du bruit à une tâche à réaction de série et au choix quintuple. Pendant une séance le bruit était limité aux fréquences au-dessus de 2000 c/s, tandis que les fréquences pendant l'autre séance étaient au-dessous de 2000 c/s. Le bruit de haute fréquence produisit plus d'erreurs de fonctionnement, quoique la différence ne devint significative qu'à l'intensité maxima de 100 dB.

Lorsque les temps de réaction étaient mesurés pour des bruits égaux, la première réaction d'une série avec le même type de stimulant était plus lente quand le stimulant était de faible intensité et de basse fréquence. Les résultats étaient différents pour des stimulants de haute fréquence ou de forte intensité.

Donc il parait que les sons les plus susceptibles de déranger le travail produisent en même temps une réaction plus rapide lorsqu'ils, eux-mêmes, font fonction des signaux, ce qui confirme l'opinion proposée déjà au sujet des effets du bruit, c'est-à-dire que l'effet est dû à la concurrence entre de différents stimulants en ce qui concerne le contrôle de la réponse.

Drei Gruppen von Versuchspersonen arbeiteten während zwei Sitzungen im Geräusch an einer Fünffachwahl-Serienreaktionsaugabe. Während einer Sitzung war die Geräuschfrequenz oberhalb, während der anderen unterhalb 2000 Hz. Das Hochfrequenz-Geräusch ergab mehr Leistungsfehler, doch war der Unterschied signifikant nur für den Fall der maximalen Intensität von 100 dB.

Wenn die Reaktionszeiten für dieselben Geräusche gemessen wurden, war die erste Reaktion einer Reihe mit demselben Reiztyp langsamer, wenn der Reiz von kleiner Intensität und niedriger Frequenz war. Dies war nicht zutreffend wenn die Reize eine hohe Frequenz oder starke Intensität hatten.

Es scheint demnach, dass Geräusche, welche die Arbeit mehr wahrscheinlich stören können, auch eine schnellere Reaktion hervorrufen, falls sie als Signale dienen, wodurch die betr. Geräuscheffekte bereits vorgeschlagene Ansicht bestätigt wird, nämlich dass der Effekt von der Konkurrenz zwischen verschiedenen Reizen verursacht wird.

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APPENDIX

Experiment I

The statistical analysis of this experiment is complex : as the variance was homogeneous, analysis of variance was employed, and a summary table is given as Table 4. As different noise intensities were given to different subjects, while each subject received two different frequencies of noise at the same

Table 4. Analysis of Variance, Experiment I

	Source	d.f.	Mean Square	F
Comparisons made between different people	Intensities (I)	2	1352	6·12†
	Order (O)	1	1281	5·80†
	Time (T)	1	127	
	I×O	2	1502	6·80†
	T×O	1	534	
	T×I	2	189	
	T×O×I	2	1246	5·64†
	Remainder (Error term for all above)	12	220·9	
	Total between subjects	23		
Comparisons made on the same people	Frequency (P)	1	833	9·67‡
	Day of Expt. (D)	1	690	8·01†
	D×I	2	703	8·16‡
	P×I	2	551	6·40‡
	Remainder (Error term for sources below the line)	18	86·1	
	Total within subjects	24		

† Means significant at 0·05 level.

‡ Means significant at 0·01 level.

Day of Experiment is the effect usually ascribed to practice : Order is the effect due to comparing subjects who started with high frequency noise and those who started with low. That is, Order is the interaction Days × Frequency. Time (T) refers to the time at which subjects were tested after arrival at the laboratory. Subjects arrived in pairs, one of each pair was tested immediately, the other after a wait of half an hour in a room away from the noise. Subjects all had both their runs at the same interval after reaching the laboratory.

intensity, different error terms are applicable to the two forms of comparison. Our main interest is in the comparisons on the same people, which are 'below the line' in the table. The various higher order interactions were insignificant and have been pooled to give an error estimate based on 18 d.f. It will be seen, firstly, that the frequency–intensity interaction is highly significant. This means that the effect of frequency depends on the intensity, as is said in the body of the paper. Secondly, the main effect of frequency is highly significant, tested against the error term: yet because of the significant interaction this does not mean that frequency always produces an effect, but only that it does so in the range of intensities here studied. If the difference between low and high frequency noise is tested for each intensity separately, using the same error estimate, it is found to be quite insignificant for the two lower intensities and highly significant ($P < 0{\cdot}01$) for the 100 dB group. Thus our conclusion is that pitch has an effect only at 100 dB, within the range 80–100 dB, and that at that level high frequency noise is worse.

It should be noted that some statistical text-books of a few years ago stated incorrectly that when an interaction is significant main effects must only be tested against that interaction and ignored unless significant by such a test. This would have left the present analysis in an inconclusive position, so it is important to note that this rule-of-thumb is now recognised as fallacious (see, for example, McNemar 1955, where the earlier edition is corrected). A design closely similar to the present one is given by Lindquist (1953) and is analysed in the way used here. To summarize the modern view on a significant interaction of the type we have found, it is likely that a repetition of Experiment I with different persons as subjects would still show more errors in high frequency noise. There is no evidence that if Experiment I was repeated using a different sample of intensity levels there would still be an effect of frequency. This statement closely follows one by Rider *et al.* (1956, pp. 13–14), in the series of papers which have called attention to the flaw in the text-books of ten years ago.

Interpretation of 'above-the-line' comparisons is more difficult, since a high-order interaction is significant. This interaction, $T \times O \times I$, shows the significance of the Welford *et al.* effect mentioned in the body of the paper. It means that the effect of intensity may appear to a greater or less degree depending on whether a given individual started the task under good conditions or not. Subjects who first meet the task early in the morning with a high frequency high intensity noise, do very badly throughout compared with others. The main effect of intensity is, however, significant when tested against the residual error term: in any case the effect of intensity has been satisfactorily established in earlier experiments by non-parametric statistics.

Equation of the different frequency noises for loudness set a difficult problem since the exposures were fairly lengthy and the resulting decline in loudness may well vary with frequency (Hood 1950). The procedure adopted was to ask the subjects to say which of the two frequency noises was louder, after both experimental runs had been completed. With the low frequency noise 3 dB more intense than the high-frequency each was judged louder an approximately equal number of times. A shift of 4 dB in either noise gave all judgements in favour of the more intense noise. These results agree reasonably well with the curves relating loudness to spectrum for various noises given by Pollack (1952).

Experiment II

The initial matching of the sounds for loudness was done in the following way. A 2-sec burst of one noise was followed by 3 sec of silence, and then by a 2-sec burst of the other noise, and the whole cycle then repeated twice more. The subject was then asked which noise was louder. This routine was first carried out with the noises at equal physical intensity, and the low frequency noise was then attenuated 4 dB if the subject regarded it as louder, or increased 4 dB if the reverse was true. Successive shifts of 4 dB were made till the equality point was passed, and a judgement then taken at a 2 dB interval between the two values giving opposite judgements. For testing purposes the low frequency noise was then left at the 1 dB stop between the last 2 dB judgement and the nearest opposite judgement. This bracketing procedure was adopted in order to give an equal-loudness value with few stimulus presentations: in the majority of cases only three presentations of the comparison cycle were sufficient.

The *reaction times* were divided for each subject into the first, second, etc. in the groups of five. For each position within the group the median time was taken for each subject, as the median is more normally distributed than the mean for unpractised subjects. Thus five scores were obtained for each subject with each type of stimulus, and the means of these scores are the figures given in Table 3. For comparing the first reactions in the group of five with the last reaction straight-forward t tests for correlated means were carried out with d.f. $=n-1$. For comparing scores for reactions to high frequency stimuli with those to low frequency ones, an analysis of variance was carried out. The variance attributable to subjects, to the stimulus given first, and to the different stimuli was extracted, and the latter component tested against the residue with d.f. $=n-2$. The significances are given in Table 5.

Table 5. Significance for Experiment II Results

Comparison	Group	P
First reaction slower than fifth	75 dB, Low frequency stimulus	$<0{\cdot}01$
	75 dB, High frequency stimulus	$0{\cdot}10>P>0{\cdot}05$ ($t=1{\cdot}91$)
,,	75 dB, both stimuli pooled	$<0{\cdot}002$
,,	100 dB, both stimuli pooled	$>0{\cdot}10$
First with high frequency faster than with low frequency	75 dB	$<0{\cdot}02$
,,	100 dB	$>0{\cdot}10$

The comparisons to be made in this experiment were decided before it was carried out, on the basis of the preliminary experiments. This is important because there are a number of other comparisons which might be made, and if those in Table 5 had been picked out *post hoc* it would have reduced their significance. It is also worthy of note that not only the median response times but also the shortest and longest ones followed the general pattern shown in Table 3.

CHANGING PHYSICAL DEMANDS OF FOUNDRY WORKERS IN THE PRODUCTION OF MEDIUM WEIGHT CASTINGS

By H. Scholz

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Systematic investigations with physiological methods in foundries have shown that even in highly mechanized work, high physical demands may exist. By the same methods, ways for lightening human work can be found, which not only do not decrease productivity, but in many cases substantially increase it.

In the Federal Republic of Western Germany more than 200 000 men are working in about one thousand iron, steel and tempering foundries, most of which have not yet joined in the rapid mechanization of the last few years. For more than a year our institute has been carrying out extensive investigations in order to evaluate the degree of working stress in foundries (Scholz and Blümel 1956). With the aid of industrial physiology, the burden of labour can be estimated quantitatively and related to the possibilities of human capacity for work (Christensen 1953, Lehmann 1953, 1956, Lehmann *et al.* 1953, 1955, Lundgren 1946).

The following methods were used :

1. Studies of the progression of work, i.e. time studies throughout the shift as developed by Graf (Lehmann *et al.* 1953).

2. Measurements of the intensity of work ; that is to say of the amount of energy expended (basic stress), determined by measuring the consumption of oxygen with the MPI-calorimeter.

3. Measurements of the extent of muscular fatigue (accessory stress) : this stress does not become evident by measuring the expenditure of energy alone. Fatigue due to an unsufficient oxygen supply of the muscles, especially, when these are maintained in continuous contraction, is shown in a rise of the heart rate. The pulse rate was observed during the whole shift by means of an electronic pulse counter (Müller and Himmelmann 1957).

4. Measurements of the bodily performance capacity (Müller 1950).

5. Measurements of additional strains by noise and heat. Intensity of noise was recorded by the Rohde and Schwarz-phonemeter combined with a Siemens-octave-sieve for frequency-analysis.

Our investigations have been carried out in seven foundries at more than one hundred different operations ; in every factory the research group, including about 10 staff members, remained for about five weeks.

The following communication intends to point out the influence of rationalization on man, especially the fact that the limiting factor in production always should be the worker's maximal endurance and not the production-capacity of the machine to be operated by the worker. By our investigations we were able to show that the extent of the physical demands of foundry workers is not dependent in all cases on the degree of mechanization of the foundry-equipment. The introduction of new methods has not always simultaneously

relieved the human factor. We found that physical strain on man in a foundry is heaviest in the case of castings of medium weight, that is weights between a few and about one hundred kilograms. That is true for moulding as well as for casting.

A healthy man can metabolize a maximum of 4·800 kcal per day when working daily. This means that after personal requirements are satisfied, 2·500 kcal are available for the performance of occupational tasks. With this as the maximum, 2·000 kcal may be taken as the normal performance limit (Lehmann 1953, Lehmann and Graf 1956).

In *old-fashioned* foundries with mass production of medium size castings, we measured work-calories to the extent of 2900 calories per shift, values which considerably exceed the normal performance limit. Yet, in spite of such high strains, often only a few short rest pauses are introduced into the working time. The total duration of these goes down to 8 per cent or still less of the working time, whereas even in lighter work 10 to 20 per cent should be considered as necessary. The high energy expenditures as cited above are required primarily in machine moulding, transportation and shovelling sand.

In *modern* factories, also, having, for example, automatic sand conveyor system, roller bands, fully automatic joggling machines etc., the human performance capacity often is used to its maximum.

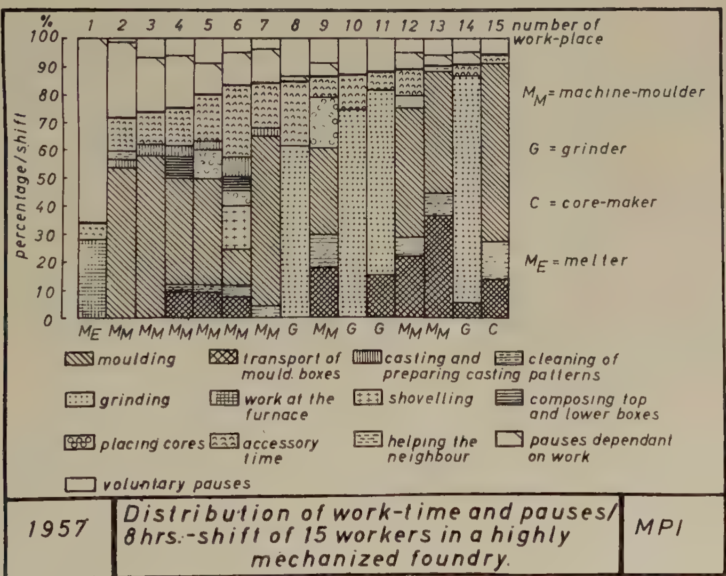

Figure 1.

Figures 1 and 2 represent the results evaluated in such a highly mechanized works. Figure 1 shows the per cent distribution of work-time and pauses in an 8-hr shift of 15 workers. The duration of the pauses (voluntary pauses and pauses dependent on work) lies between 65 per cent and 70 per cent of the whole shift-time. Figure 2 represents the basic stress (energy consumption) and accessory stress (fatigue rise of pulse rate) of these 15 workers—the men being arranged in the same order of succession as in Fig. 1. The height of the

single columns points to energy consumption between 850 and 2600 work-calories per shift. From these two figures two points emerge: (*a*) There is no correlation between length of rest pause and energy consumption. (*b*) Five of the fifteen operations demand an energy consumption beyond the normal performance limit. In four others, the exertion overloads the circulatory system in that working pulse rates are more than 40 pulses above the resting value per minute. In all, more than half the workers in the sample are overloaded.

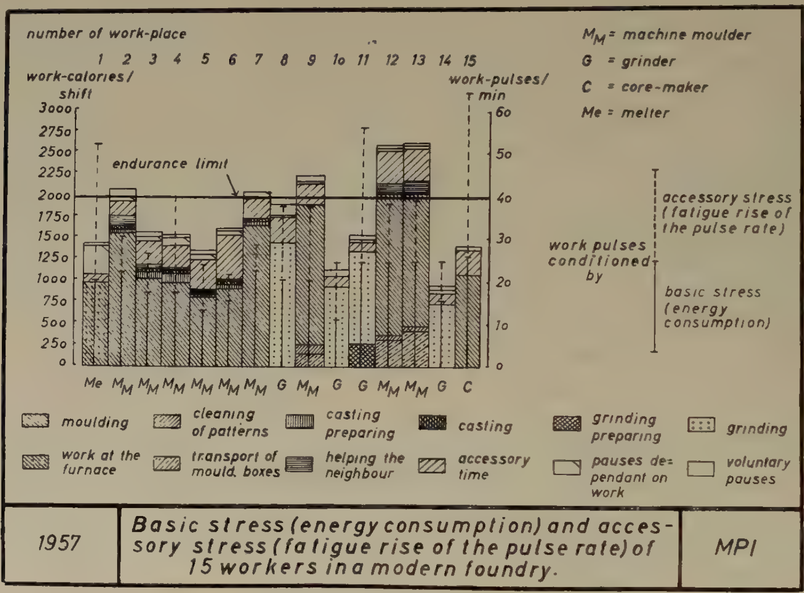

Figure 2.

Physical demands of about this level and involving about this percentage of workers were always revealed by our measurements. The main causes of such very considerable demands appear to be five in number and are listed below together with examples:

§ 1. Imperfect Rationalization of Material Handling

In one factory, standard joggling machines had been installed, but the moulding sand was not conveyed through a discharging hopper to the moulding box, but fell on to a heap, which had to be shovelled by the moulder into the moulding box. The total energy consumption amounted to about 2500 work-calories, the energy output for the shovelling performance being 700 kcal per shift. Nearly one-third of the high energy expenditure was required of a skilled workman by activities that might have been carried out by unskilled men or better by mechanical equipment. In this case, the human performance capacity by being used to its maximum was setting limits to production, and an easing of the working conditions would automatically have resulted in an increase in production.

In another case modern high-efficiency core-making machines had been installed; but the designer of these machines had forgotten to add a sand-conveyor system. Each of the women workers has therefore to feed 30 sand

boxes of about 20 kg each into the receiver at the top of the machine by hand. Again our measurements showed that the semi-mechanized transport of waste moulding sand by an electrically operated scraper with handles placed too low, required the worker to maintain a bent position for over 5 hours a day, which was extremely fatiguing.

§ 2. Severe Heat Stress

A great number of factories have installed modern high efficiency electric cupola smelting furnaces which involve strains producing a pulse rate of up to 140 per minute in the men operating them, extending over protracted periods. Again, considerable strains are caused, if no holding device is installed for grasping the melted metal from the crane ladle or for casting with the ladle or melting pot. Such operations, especially under heat stress, require sufficient and frequent rest periods. The workers must be urged to take their rest allowances during the shift ; often the management allow men to leave work before the end of the shift, if they have reached their production standards.

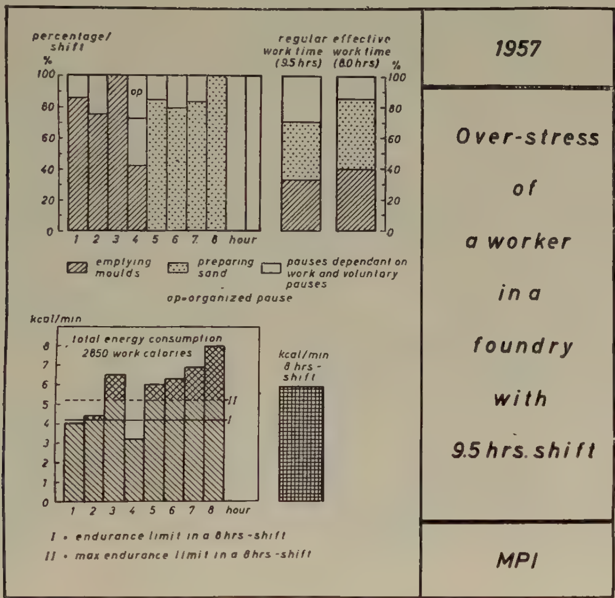

Figure 3.

Figure 3 refers to a worker who compresses his regular performance for $9\frac{1}{2}$ hours to 8 hours and leaves the factory one and a half hours too early. Referred to the effective working time of 8 hours, the rest pauses amount to only 15 per cent of the shift, the energy consumption being 3000 work-calories per shift. There must be added, however, the strain due to the radiant heat during the first four hours caused by taking the still glowing pieces from the moulds in a deeply bent position. Because of the worker's tendency to finish the operations as quickly as possible, the energy consumption shown at the bottom of Fig. 3 increases from hour to hour and reaches 8 kcal per min at the end of the shift. To correct this we have caused the worker and his group to stay at the working place throughout the shift and to take rest pauses of 15 minutes after every 45 minutes.

§ 3. Static Work due to Badly Designed Machines not Adapted to Human Use

Considerable extra static work is imposed by so-called ' modern ' but badly designed machines in the construction of which the human factor has not been taken into consideration. Thus we found that fettlers generally have a relatively low energy consumption of between 800 and 1500 work-calories per shift. To this output of energy, there must be added a stress which cannot be evaluated in calories, imposed by static working positions. The unnatural position in which the worker is obliged to carry out his work throughout the shift leads, for instance, in grinding rod straps and wheel spindles, to an increase over the eight hours in pulse rate of about 50 beats above the resting value per minute. This means that the circulation of many fettlers is under too great a strain (Fig. 4).

Figure 4.

In the case of a core blasting machine (Fig. 5) we discovered that the position of the operator's arm required to work it, was physiologically bad and that the woman operating the machine used up 1340 work-calories per shift. This means that she was on the borderline of what could be reasonably demanded from her for continuous work. Strains on the circulatory system must, however, be taken into consideration in addition to this : the pulse rate throughout the whole shift was about 65 beats per min over the resting value of which excess only 25 can be attributed to the expenditure of energy, whilst the rest, that is to say 45 beats per min must be ascribed to unnecessary static strain. It would be of great advantage in rendering the work less onerous if the two levers, namely the eccentric lever and the compressed air lever, both of which are positioned above heart level could be replaced by foot levers, and if it were possible for the operator to perform her work standing or sitting at will.

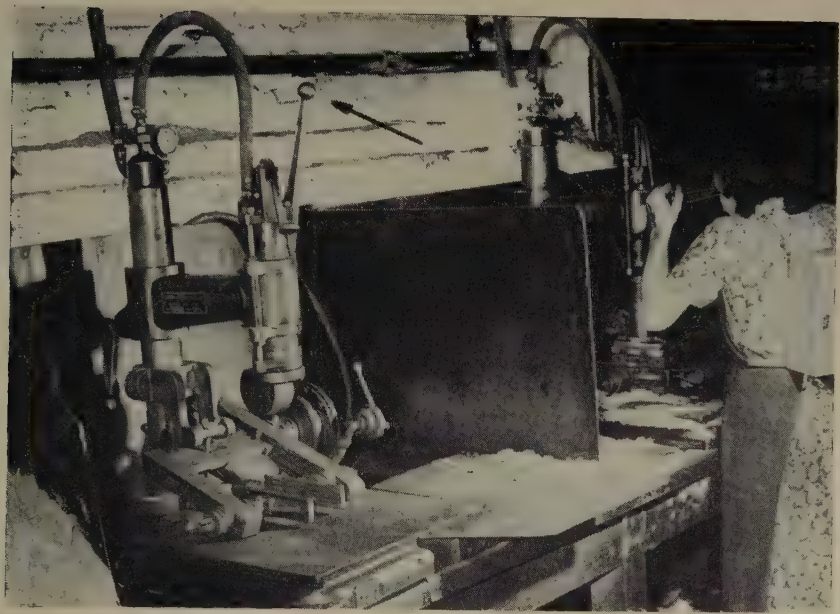

Figure 5.

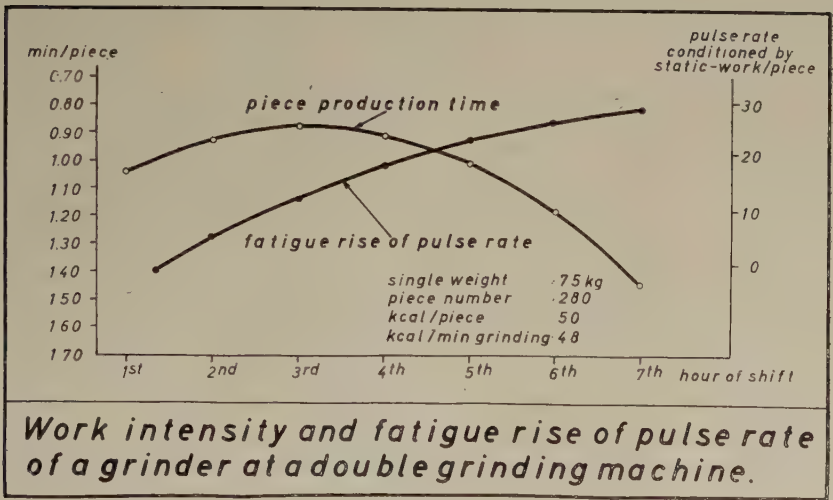

Figure 6.

§ 4. Disregarding of Rest Allowances by the Men

The influence of working without rest pauses on the output and the circulation is shown by Fig. 6. The operation is grinding at a double-grinding machine. During a shift the man normally worked 280 pieces of 7·5 kg each. The grinder began his work at high intensity, and increased it still more during the second and third hours. Then, however, the output rapidly and continuously decreased so that the piece production time in the seventh hour was about 50 per cent longer than that in the third hour. The worker tried to finish

his work—the regular shift was 8 hours—by working almost without pauses. The figure also illustrates the rise of pulse rate resulting from static strain and fatigue. It can be seen that the rate of increase rises continuously from 2 pulses per piece in the first hour to 31 pulses per piece in the seventh hour. By adding the pulses per piece resulting from energy consumption, we arrive at 58 pulses per piece above the resting value. As our fettler had over-exerted himself during the first 3 hours by working too fast and without rest pauses, it is not unexpected that the pulse rate increased to this extent. The pauses should not be taken at the end of the shift but should be distributed all over the whole shift, a few minutes at a time.

§ 5. Noise Stress

In highly automatic joggling machines, grinding machines and other equipment, we found noise intensities lying between 100 and 120 phons. We succeeded in diminishing the noise of double grinding machines from more than 100 phons to 90 phons by laying a 2 mm rubber mat between the support bed and the supporting surface of the machine.

We turn now to examples of how by considering these various sources of stress together, we were able to advise foundries on whether methods they were planning of rationalization and mechànization were capable of increasing producton, whilst at the same time lightening the task of the worker and, if so, to what extent. In one case, at a works not having an automatic sand conveyor system, 2800 work-calories per shift were expended by the men in casting wearing plates. It was imperative to reduce this very high consumption and to bring it nearer to the standard of 2000 work-calories. This could only be effected by mechanization extending to specially onerous operations lying outside the actual process of casting. The work of shovelling is particularly suitable for this. Automatic feed of filling sand would if the volume of production remained as hitherto (24 pieces per shift) mean a reduction of working strain only to 2250 work-calories per shift, whilst the use of the time saved in order to increase production by perhaps 12 per cent would result in an output of 2500 work-calories per shift. From this it is clear that automation of the filling sand feed alone would not result in reducing working stress to the desired extent. In order to do so it would be further necessary to make the moulding sand feed automatic, which would effect a reduction of 250 kcal per shift.

In another case we established through our measurements that incorporating automatic sand feed in the process of casting small furnace parts would lead to an increase in production of 17 per cent, whilst, at the same time, decreasing the unduly high consumption of energy of the foundry-men (2600 work-calories).

A further example of what may be attained by rationalization aimed at the individual may be given. In one factory we compared the production and energy consumption of the workers at disc wheel moulding by hand, by a standard joggling machine and by a fully automatic joggling machine. Figure 7 represents the results. Using a standard joggling machine the energy consumption per wheel moulded decreased by nearly 50 per cent. When a fully automatic joggling machine was put into use, the energy output amounted to only about one-third of that required for production by hand.

The net result was that though the energy consumption amounted in all three cases to about 2000 work-calories, the production rose by about 100 per cent with each increase of mechanization. One reservation must, however, be made. The fully automatic machine had been installed only two months

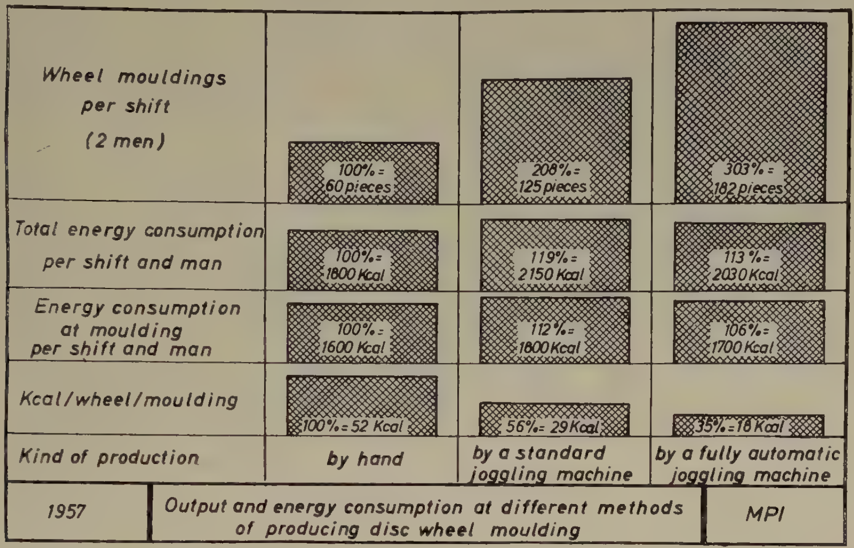

Figure 7.

before the beginning of our investigation and the worker was paid by the hour, as the piece rate was not yet fixed. It is to be feared that when this is done he will exceed the normal energy consumption for heavy work in aiming at a thicker pay envelope.

Les études systématiques conduites dans des fonderies avec des méthodes physiologiques ont montré que de grandes exigences physiques peuvent exister même aux cas du travail très mécanisé. On peut employer les mêmes méthodes pour trouver les moyens d'alléger le travail humain, qui non seulement ne diminuent pas la productivité, mais la parfois augmentent d'une manière prononcée.

Systematische Forschungen, welche mittels physiologischer Verfahren in Giessereien ausgeführt wurden, zeigten, dass hohe physikalische Ansprüche sogar im Falle äusserst mechanisierten Arbeit vorkommen können. Dieselben Methoden ermöglichen es, zwecks Erleichterung der Menschenarbeit Wege zu finden, durch welche die Produktivität nicht nur nicht vermindert, aber in vielen Fällen sogar wesentlich erhöht wird.

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A COMPARISON BETWEEN THE RESULTS OF THREE DIFFERENT METHODS OF OPERATOR TRAINING

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A new type of operative training is described in its application to the mending of worsted cloth. The method resulted from the identification of the essential difficulty in mending as perceptual in nature but as not primarily dependent upon 'good eyesight' as normally understood. Special provision was accordingly made to enable trainees to master the perceptual task thoroughly. Results of this method were shown to be superior to those of the traditional 'sit-by-me' and T.W.I. methods, both in an experimental training school and in industry.

§ 1. Introduction

Operator training is coming to be regarded in industry as of great importance in the achievement of high productivity and output and although a variety of training techniques exist at the present time (NIIP 1956), comparison between the effectiveness of different methods of operator training has not received much attention. There is, it is true, experimental evidence from the laboratory regarding the influence on efficiency in learning of certain factors such as the massing and spacing of practice, 'part' and 'whole' learning, reward and punishment, competition and knowledge of results. Yet, to the industrialist who enquires whether one recognized method of operator training is better than another, there is no answer which can rest fairly and squarely on direct evidence.

Perhaps the most significant contribution to the subject so far has been made by Seymour (1954, 1955, 1956), who has shown that the part method of training is more effective than the whole method only where the parts involve high demands for perceptual interpretation and control. The parts of an operation may be learned in successive order or it is possible for those making high perceptual demands to be learned separately before the task is tackled as a whole. The former method Seymour termed the Progressive Part Method and the latter the Isolation method.

It is tempting to equate the whole method with the Exposure Method or traditional method of teaching a task whereby the trainee learns by working alongside a skilled operator, the Progressive Part Method with T.W.I. and the Isolation Method with a method sometimes used by consultants in the field of training. However, we cannot be sure whether the drawing of the parallels between the experimental methods and the 'field methods' is justified and indeed Seymour draws no such parallel himself. If this is so we are left with no actual case on record where recognized industrial operator training methods have been compared under controlled conditions.

§ 2. The Present Investigation

It is held in the Yorkshire Wool Textile Industry that one of their most highly skilled tasks is that of mending the unfinished cloth. Faults made by the spinners or weavers have to be detected and removed, and the cloth invisibly mended before it goes for final processing and dyeing. A tour of some of the mills revealed that training a mender sometimes took as long as two years. In most mills one was told that only *some* menders were able to mend the really fancy weaves. Others who have been in the industry for many years still have to be assisted by the supervisors. The ability to mend these more difficult weaves was held to be a ' matter of individual eyesight '.

In order to understand the fundamental difficulties underlying the acquisition of this skill, one of the authors spent a week in a mill learning to do the task. From this experience and from discussions with and observation of both experienced menders and trainees, we formulated an experimental training method, based on principles derived from the results of some laboratory work. To assess its value in relation to the accepted methods of training in the mills, we set up a Training Centre where three sets of school leavers (equated as far as possible for initial ability) were trained under the same external conditions for a period of three months, by each of three methods.

1. The Exposure or ' *Sit-by-me* ' method, refers to the traditional arrangement whereby a trainee works alongside a skilled worker who gives instruction and help when and how he or she thinks fit.

2. *T.W.I.* (Training Within Industry) is the method made available through the Ministry of Labour and National Service and which relies on job breakdown, instruction and practice by stages. It is, of course, too well-known to require further description.

3. The new *Experimental* Method was based on the theory that successful performance of a difficult industrial task depends on the initial acquisition not only of the correct method or the required motion pattern but of the correct perception of the cues which make the desired motion pattern possible. This perceptual skill cannot be delevoped by verbal methods of instruction and training, but rather by conditioning the trainee to the important cues of the task through successive presentation of tasks in which the essential perceptual stimuli are emphasized or the response to these stimuli facilitated. These tasks are given in accordance with the progress made by the trainee. If the task is difficult it will be made easier and when it becomes easy it will be made more difficult. Experience, however, is gained in a much shorter time than it would be ' on the job ' and is always ' correct ' experience. In the case of mending, this ' correct ' experience was gained, for example, by allowing the trainee to mend only specially woven large scale weaves where the interlacings were easily visible. Missing threads had to be sewn in and it was found that verbal description of the weave (which had proved to be so difficult for trainees to follow) was quite unnecessary. To enable the trainer to assess the trainee's understanding of the weave, the trainee had to make up her own weaves with elastic thread on a light alloy frame (Fig. 1). The transition from making up an elastic weave to mending a giant weave was easily accomplished and gradually, as the trainee became more confident, the size of the weave was reduced. Finally the normal sized weave was sewn, first with and later without

the aid of a magnifier. By this gradual acquisition of 'correct' responses the trainee did not have to learn anything which she would subsequently have to 'unlearn'.

In order to minimize 'overlearning' on any one product so as to effect easy transfer of the initial training when new and related types of product occur, the trainees were given all the four basic weaves together for comparison and for practice on each from the very commencement of their course. (These four weaves are shown in Fig. 2.) In this way they learnt to understand each weave in relation to the others, rather than learning to mend one weave at a time 'by rote'. It had been customary in the industry to provide during the first few weeks—or in some cases for three months—only that weave which was most commonly used in the mill.

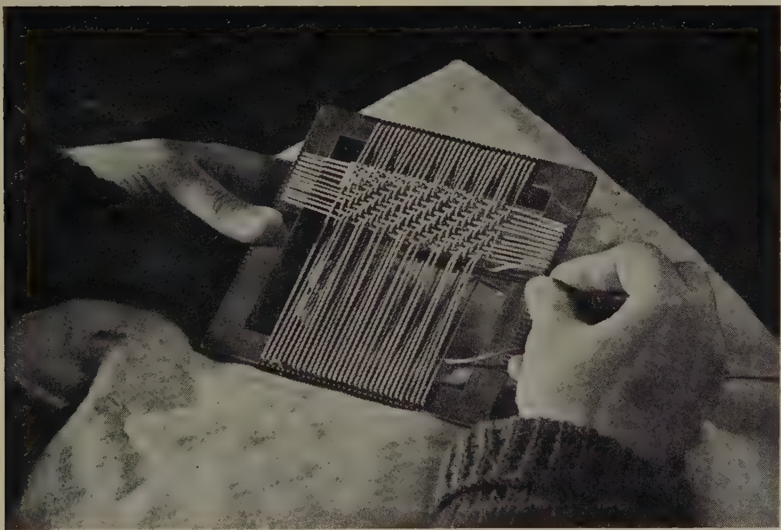

Figure 1. A trainee making up a 2×2 Twill weave with elastic thread on the light alloy frame.

Several firms, all of whom dealt in similar types of worsted cloths, provided the trainees and paid their wages. Records were kept of their initial ability on a battery of tests (see Belbin *et al.* 1956) together with their attainment at the end of each fortnight on the mending skill in terms of speed and accuracy. The fortnightly tests became progressively more difficult in terms of length and type of weave and of number of picks to be replaced. Production records for the trainees' first two years in industry are also being kept. Difficulties arose in recruiting trainees for the Exposure group. Knowing that new methods were available at the Wool Textile Employers' Council, firms showed considerable reluctance to send trainees who were destined for no more than the traditional methods of training. Whereas ten girls had been selected from applicants for each of the other two courses, it was only possible to recruit four girls for the Exposure course and of these one left before the end of the course. In order, therefore, to make reasonable comparison between the three methods of training, other worsted firms were approached with a view to giving the attainment tests to any school leavers who were being trained by the Exposure

Method in the industry at that time. Five trainees were offered and they were given the initial selection tests and the 6th and 12th week attainment tests. These girls seemed to be a selected group whose results are likely to present a more favourable picture of the outcome of this type of training than we should expect usually to encounter. The evidence for this lies in the fact that in order to obtain the five additional trainees fifty firms had to be approached : it seemed clear that only firms well pleased with the progress of their trainees were willing to let them undergo the tests.

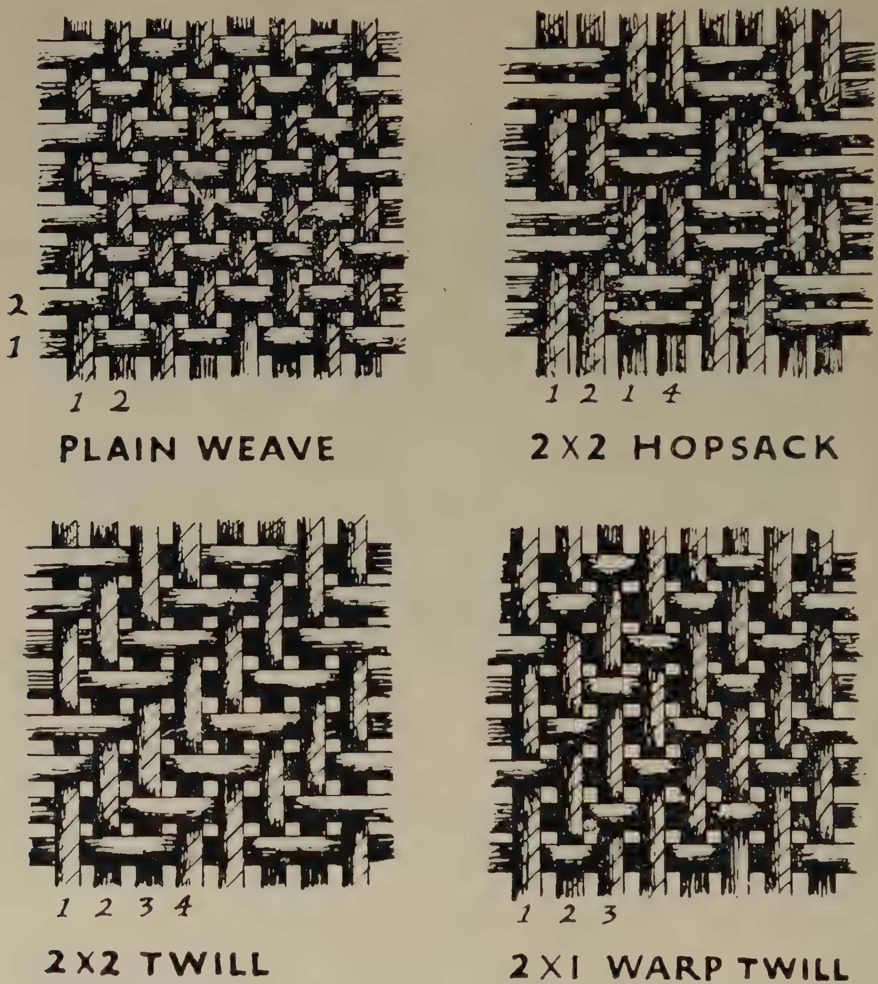

Figure 2. The four basic weaves used in the Mending Experiment.

Attempts were made to keep the variation between *trainers* to a minimum by taking the best trainers available for each type of training. For the Exposure Method the group at the training centre were taught by a highly experienced mender and trainer. For the T.W.I. Method two highly skilled and experienced supervisors were trained and afterwards themselves supervised, by the Ministry of Labour Regional Training Officer.

The choice of a trainer for the Experimental Method was more difficult. It will be appreciated that a training scheme of this type could only be successfully administered by someone fully conversant with the principles upon which the scheme was based. The educational level of menders and mending trainers in the industry is low and the age level high, and it seemed unlikely that we should obtain a trainer who would fully understand the purpose of our methods. For this reason it seemed preferable to choose someone of the required educational and intelligence level who was not a skilled mender but who would initially spend some little time in learning to mend. The woman chosen to supervise the course spent one week learning the skill and a further week becoming familiar with the principles underlying the training scheme. She was assisted in the task of actual instruction of the trainees by two demonstrators who had been recruited from industry. At first sight it may seem that there are serious disadvantages in employing a trainer who has only a very limited experience of a skill. But while these disadvantages should not be minimized there are attendant advantages. Our preparatory investigations into the methods and achievement of trainers in the mills had underlined the remoteness of the skilled worker from the experience and understanding of the young trainee. The skilled mender can easily see the interlacings and she does not fully appreciate the trainee's difficulties. The skilled worker regards the pattern as a sort of mathematical formula, the intricacies, peculiarities and characteristics of which she likes to discuss with other workers. But the trainee is less concerned about the make-up of the weave. Hers is a more perceptual problem—of seeing the configuration. The long experience of the trainer is not therefore very useful because the experience is largely inappropriate to the problems that the trainee has to face in the early stages.

§ 3. Results

3.1. *Quality*

The quality of the mending was assessed on a ten point scale by two independent, experienced menders. Most of the trainees in each of the groups achieved a satisfactory quality. The difference in quality between the work of the groups on the 12th week test was only slight although the Exposure group was a little poorer than the others. Thus, if we consider the number of scores under 6 marks out of 10 on any of the eleven weaves (i.e. something lower than 'good standard' rating), the Exposure Group had 22% of their marks in this range, T.W.I. had 13% and Experimental 10%.

3.2. *Times Taken to Mend*

Clearer differences between the groups appeared in the times taken to perform the test mends. It should be noted that these results were in the same direction as those for quality so that there is no question of quality and quantity being inversely related.

Where a trainee completed more than half of a mend incorrectly or was unable to tackle it, no time was assigned to the performance but it was instead placed in a category represented in the figures which follow as 'Unable to do'. The numbers of mends falling into this category out of the eleven set each subject in the 12th week test showed a clear differentiation between the three

methods, being 15 among the eight subjects trained by the Exposure method, 5 among the ten T.W.I. subjects and one among the nine Experimental subjects.

It is not possible, because of the ' Unable to do ' category to give summated times but the results shown in Fig. 3 for a simple weave and in Fig. 4 for a complex one are representative of results at the end of the course. It can be seen that the median times for the Experimental method are substantially lower than for the others. The target times shown in these figures were based on a time study of experienced menders.

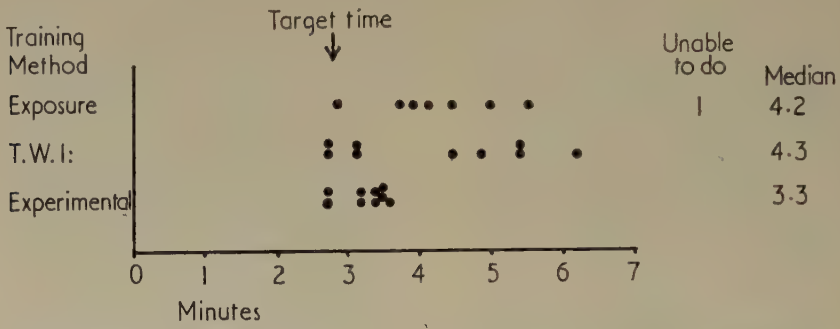

Figure 3. Time taken to mend 6 in. of a weave (1 × 1 Plain Single) at Week 12.

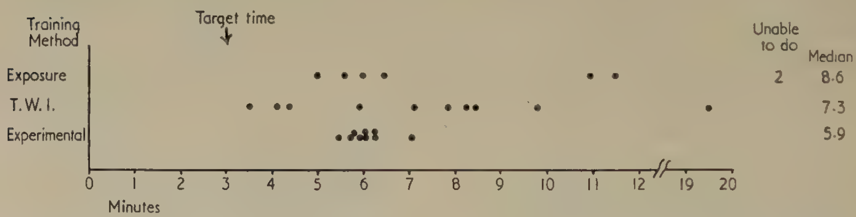

Figure 4. Time taken to mend 6 in. of a weave (2 × 2 Broken Twill Single) at Week 12.

The most notable point of difference between the results for the three methods shown in these figures is the comparatively low scatter of times in the Experimental group. It might be said that by the end of the Courses all girls trained by the Experimental Method had attained a reasonable standard. With T.W.I. training some were trained to a very good standard but others were very poor. With the Exposure Method training, only one girl was of very good standard. In addition to a lower scatter of final scores after the Experimental training, only one girl was of very good standard. In addition to a lower scatter of final scores after the Experimental Training, there was also less variation in the performance of any one girl on the mending of her 11 different weaves. The other two training methods showed a wide variation of performance for any one individual. For example, a number of the T.W.I. and Exposure method trainees were unable to mend the more difficult patterns at all ; others found great difficulty in mending weaves where there were two of three picks missing. The Experimental Method trainees, however, did reasonably well on all these more difficult tasks. They were also able to tackle a new weave reasonably well very quickly after meeting it. In the other groups, however, only *some* of the trainees could tackle new and more

difficult weaves. Figures 5 and 6 show comparative figures for work on a new weave.

It might be argued that the Experimental Group provided better initial material for training. It could be seen from progress graphs, however, that their final performance was more dependent on the training programme than on their initial ability. For example, Fig. 7 shows performances at weeks 4 and 12 of the course. It will be noted that the Experimental group were on

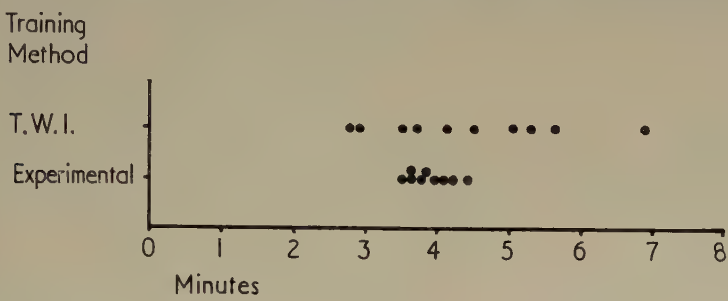

Figure 5. Time taken to mend 6 in. of a *new* weave (2 × 2 Hopsack Single) at Week 6.

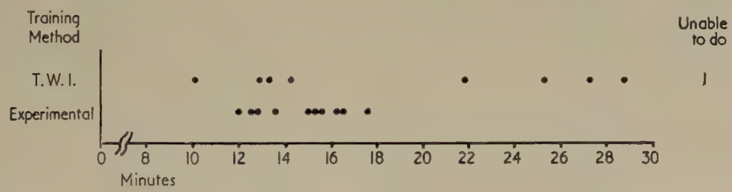

Figure 6. Time taken to mend 6 in. of a *new* weave (2 × 2 Twill Treble) at Week 10.

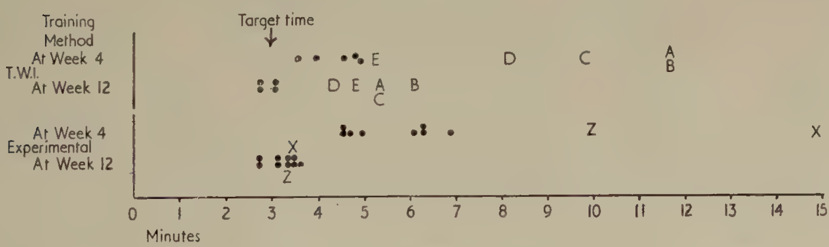

Figure 7. Contrast in final attainment of ' Bad Starters ' (indicated by letters) after two different training methods : time taken to mend 6 in. of a weave.

(One girl was absent at Week 4 in group trained by Experimental Method. One girl was absent at Week 12 in group trained by T.W.I. Method.)

the whole worse at Week 4 than the T.W.I. group. At the end of the 12th week, however, they were considerably better. In the T.W.I. course those who were bad starters remained comparatively bad throughout the course. With the experimental training, however, it can be seen that those who started badly and in fact in some cases remained comparatively poor for as long as four weeks, attained a good standard by the end of the training programme.

The initial battery of selection tests provided very little guidance as to final performance. For example, those who were best on the trade test (a simple sewing task) were some of the worst menders after twelve weeks. A further

and very interesting contrast emerged between the results of the three courses in relation to these initial selection tests. Whereas it may be said that some of the tests showed positive correlation with final performance in the 'Sit-by-Me' and to a lesser extent in the T.W.I. Courses, when we look at the Experimental group, these selection methods showed no substantial positive correlation with final performance. The correlation between some of the selection tests and the final mending results in the different courses are shown in Table 1.

Table 1. The Relationship between some of the Selection Test Results and Final Attainment in the Different Courses

	Sit-by-Me ($N=8$)	T.W.I. ($N=10$)	Experimental ($N=9$)
Kohs Block Test			
Median selection test score	27	22	30
Product-Moment correlation of individual attainment test results and selection test results	+0·68	+0·45	+0·22
Finger Dexterity Test			
Median selection test score	76	69	65
Product-Moment correlation of individual attainment test results and selection test results	+0·6	+0·38	−0·79
Paper and Pencil Cross-Out Test (Spotting discrepancy in words and figures)			
Median selection test score	C	D	C
Product-Moment correlation of individual attainment test results and selection test results	+0·91	+0·8	+0·15

§ 4. Application in a Factory

After a certain amount of revision, the Experimental Training Method was applied in a Factory. The mill chosen was particularly appropriate as the trainer was an experienced mender who had received a T.W.I. training and applied it in the T.W.I. Course at the Training Centre. She was now trained in the Experimental Method. The advantages of using her services in this particular firm were that not only could the results of a T.W.I. training scheme be compared with that of the Experimental training scheme under the same factory conditions—since she had recently trained girls in this factory with the T.W.I. method—but that we should no longer have the personality variable of a different trainer for the two schemes. Thus the results of two different training methods could be compared under almost identical factory conditions.

The twelfth week attainment test used previously was given to both groups at the end of the Experimental Group's training period, as follows:—

		Length of training in weeks
T.W.I. trainee	A	15
	B	29
	C	29
	D	31
Experimental	E	10
	F	12
	G	12
	H	12

When the mends were ranked for quality by independent raters, the Experimental group came higher than the T.W.I. group. They produced 23 mends of a passed standard, whereas the T.W.I. group produced 10 passed mends. The median times for mending 6 in. of all the test pieces were lower for the Experimental Group, as shown in Table 2. It may be reasonably said, therefore, that the Experimental group was trained to a better level both of speed and quality in a shorter time than the T.W.I. group. In addition, the Experimental group was able to mend fancy weaves which the T.W.I. group was unable to do—i.e. the Experimental Group had been better trained for adaptability. There was again less variation between best and worst trainees after the Experimental method.

Further applications of the new training method have enabled another factory to start a training department without the services of a trained mender, and a third factory to reduce the training period for menders from two years to three months without loss of very high quality.

Table 2. Median Times in Minutes for Mending 6 in. of a Weave in the Week 12 Test (Training in a Factory)

Weave		Course T.W.I.	Course Experimental
2 × 1 Twill	Single	21·15	9·25
	Double	27·10	26·10
2 × 2 Twill	Single	3·75	3·50
	Double	10·53	8·00
	Treble	19·75	13·40
2 × 2 Hopsack	Single	5·10	3·20
	Double	9·95	6·30
	Treble	15·85	11·30
1 × 1 Plain	Single	3·60	3·20
	Double	13·00	7·70
		(15 to 31 weeks training)	(10 to 12 weeks training)

§ 5. Follow-up Returns from Industry

Monthly returns have been collected from the Mills where the girls have been working since leaving the Training Centre. These have shown details of the type and number of weaves mended per week throughout a year, together with the supervisors' comments and notes on difficulties encountered. Table 3 shows the average weekly production three months after entering industry. The different firms are indicated and comparison is made with the ranking on performances at the training centre. The results are shown for the T.W.I. and Experimental groups only, as production records were not available for the whole of the Exposure group. Surprisingly and somewhat disappointingly there was little relationship between the final performance of the trainees at the Training Centre and their production rate. Although the Experimental group tends to do better than the T.W.I. group, the average weekly production bears more relationship to the employing firm than it does to the training method used or to the girl's performance at the end of her training period. For example, the group of girls in Factory B had achieved very similar production at the end of three months in industry yet their ranking in the training centre ranged from first to sixteenth. On the other hand all girls in firm E had the lowest production, although one girl was second and another fifth in

the training centre ranking. We have accounted for this in the following ways. Some firms permit a lower standard of work; accordingly a greater number of pieces are burled and mended than where higher standards are demanded. In other firms it has been noted that the general discipline of the menders is not good : in these firms the production rate is low, even of some girls who had done extremely well in the Training Centre. In other cases, the system of payment affects production.

Table 3. Average Weekly Production Three Months after Leaving the Training Centre

Firm	Average weekly production in pieces	T.W.I. training	Experimental training	Ranking assessed on mending performance in the training course
A	4		√	10th
B	3¼		√	3rd
B	3	√		1st
B	3	√		4th
B	2⅔		√	12th
B	2½	√		13th
B	2¼		√	11th
B	2¼	√		16th
C	2¼	√		15th
C	2		√	6th
D	1¾		√	9th
D	1½		√	Absent for test
C	1½		√	7th
C	1¼		√	8th
E	1¼	√		2nd
E	1	√		5th
E	¾	√		14th

At the end of a further three months in industry we noted that the trend of each girl's progress was also very much related to the firm in which she worked. For example, when we recorded individual improvement during the first six months in industry, we observed that in

Firm B—all but one had increased output by one piece per week. One had achieved half a piece increase.

Firm C—three girls had dropped in output by half a piece. One was at the same level as at the end of training.

Firm E—two girls had reduced output by half a piece per week. One had barely improved on her position after training.

It seems that the full benefits of training are only felt if optimum conditions prevail subsequent to the training period.

§ 6. The Training of Older People

The Experimental Method has now been applied to the training of older people. It has generally been assumed in the industry that the mending skill is a matter of good eyesight and for this reason that it is an unsuitable task for older people. Some initial results, to be reported in a later paper, show, however, that older people can be adequately trained by the new method.

§ 7. Discussion

The results of applying the Experimental Method of Training in a Training Centre, in Industry and with older people have shown that it is possible to teach the skill of worsted mending to a higher standard and in a shorter time than had hitherto been thought possible.

The main point of divergence between the results of the different training methods is the reduction of individual differences after the Experimental training, and we should now consider how best we can account for this reduction.

With a training method based on demonstration, such as the Exposure Method, there is no way of ascertaining the trainees' difficulties in learning. The supervisor herself is very remote from her own training and has long forgtten her own difficulties at the time of learning. Even if she remembers them she is unlikely to be able to eliminate them entirely for the trainees merely by letting them imitate her own performance. Demonstration presents a visual picture of what is required without assisting in how to acquire it. There is, for example, no control over the visual perception of the task, which in mending is such an important component. T.W.I. takes training a step further by attempting to emphasize the key points of difficulty. The trainer is responsible for analysing these points of difficulty and the trainee has to repeat verbally what he has to do in order to show that he fully understands the instructions. But this in no way ensures that the trainee is able to *do* it. Finding out what parts of a task are difficult is, of course, important, but it is not the same thing as understanding the nature of the difficulty and knowing those methods by which that difficulty might be overcome. It was for this reason that before designing the Experimental training programme we attempted to learn the skill for ourselves and thus to point up the main difficulties encountered in the learning process.

The central difficulty in mending appears to be a perceptual one. The current opinion of supervisors and management is that the ability to mend is a matter of good eyesight. That this is not so is suggested by the number of older people who have worked at mending in the mills for many years in spite of their poor eyesight. Further, all trainees in the training centre were given a very stringent eyesight test by a group of opticians. Those with the worst mending performances were not those with the worst eyesight. In addition, we found that industrial magnifiers were most helpful during the initial stages of learning the skill, but once the task had been understood the trainee was able to 'see' without the aid of the magnifier. 'Not seeing' was in fact 'not understanding'. That the experimental groups had grasped the skill and had mastered the perceptual component of mending was apparent from their adaptability to new and difficult weaves.

The method of developing perceptual skill used for the Experimental group consisted of a careful control over the perceptual requirements of the task, which were varied according to the progress of the individual trainee and were taught without verbal instructions which would have had to be translated into motor skill. This method cannot very easily be classed under any existing type of training method. It cannot be classed with either the Progressive Part or the Isolation Method as described by Seymour, since these demand in their various ways a separation of the components of the operation. In our case the task was not so much broken up as modified. This type of modification of the

task which was carried out in order to control the cues seems in line with the suggestion of Annett and Kay (1956) : the skilled man, they say, responds to fewer cues than the unskilled. If, therefore, irrelevant cues can be eliminated and the trainee is left with only those on which the skilled operator depends, there should be an economy in time and effort in the training period. In addition the trainee is less likely to make errors if irrelevant cues are minimized ; these errors themselves often provide erroneous cues to further incorrect response. By magnifying the interlacing structure of the weaves we controlled the cues to correct responses, since it was almost impossible when mending the different types of large-scale weave to make an error.

This control of cues would appear to be of special importance to persons who have difficulty in comprehending and organizing the requirements of highly skilled performance. It would appear, therefore, to have special application to the training of unskilled labour, mental defectives and older persons.

On décrit un nouveau type d'instruction d'ouvriers pour le cas de la raccommodation de l'étoffe de laine peignée. Cette méthode est basée sur la supposition que la difficulté fondamentale de raccommodation est de nature perceptuelle, mais qu'elle ne dépend pas en premier lieu de la ' bonne vue ' comme on l'accepte généralement. Par conséquent on a pris des dispositions pour assurer que les personnes en train d'être instruites apprennent à fond le travail perceptuel. On a montré que les résultats de cette méthode sont supérieurs à ceux des méthodes traditionnelles dites ' sit-by-me ' et T.W.I., dans l'école de l'instruction expérimentale ainsi que dans l'industrie.

Es wird ein neuer Typ der Arbeiterschulung beschrieben, in Anwendung auf Ausbesserung von Kammgarngeweben. Das verfahren basiert auf der Annahme, dass die Hauptschwierigkeit in der Ausbesserungsarbeit der Wahrnehmungsgruppe a gehört, wobei sie jedoch nicht in erster Linie vom ' guten Gesicht ' abhängt, wie dies allgemein angenommen wird. Spezielle Vorkehrungen wurden daher getroffen, damit die Schüler die Wahrnehmungsaufgabe gründlich beherrschen. Es wurde gefunden, dass die Ergebnisse dieser Methode denen der üblichen ' sit-by-me '- und T.W.I.-Verfahren überlegen sind, und zwar sowohl in einer experimentellen Ausbildungsschule, als auch in der Industrie.

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THE EFFECTS OF INCREASING SKILL ON CYCLE TIME AND ITS CONSEQUENCES FOR TIME STANDARDS

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It has been found that when a work cycle is repeated many times or a number of examples of the same product are made, the time required per cycle or product falls progressively over very long periods even among skilled and experienced operatives. This fact complicates the setting of time-standards for production work. Formulae are provided by means of which due account of the fall of cycle time may be taken when making time-studies and which provide a fundamental quantitative approach to the estimation of skill resulting from experience.

§ 1. Introduction

A considerable amount has been written upon the effects of the increasing skill which results from doing the same thing repeatedly. The literature on the subject includes indications, usually accompanied by results from laboratory research, regarding the magnitude of the influence of increasing familiarity with an operation on the time required for its performance. The subject has as yet, however, hardly made its way into the textbooks on time-study and rate-fixing.

The usual advice given in such books is to make observations on operatives of ‘ normal ’ skill. In practice, however, the low level of skill that is found among new operatives is in part reproduced among experienced operatives each time an operation is changed as, for example, when a new ‘ model ’ is produced of an existing product. This makes it impossible to assess time-standards accurately when changes have recently been made even if experienced operatives are studied. In many firms, the trouble is got over by adjusting normal time-standards to the expected increase of skill by the application of ‘ learning curves ’ (Cahen 1938, Hadley 1950).

Even in batch-production by experienced operatives, the influence of familiarity with the work can become a factor to be taken into account when fixing time-standards—its neglect can lead to gross error. It is this aspect of the matter with which this paper is concerned.

§ 2. The Fundamental Formulae

Of recent years, the adoption has more than once been recommended of relationships of the following forms for the algebraic expression of the gradual fall in the time required per consecutive work cycle (or product) (Rigdon 1944, Hirsch 1952, Schmidt 1952).

$$T_s = \frac{T_1}{s^m} \qquad \text{. . . . . (1)}$$

$$T_{nc} = \frac{T_1}{n} \sum_{s=1}^{n} \left(\frac{1}{s^m}\right) \qquad \text{. . . . . (2)}$$

or sometimes, instead of (2)

$$T_{nc} = \frac{T_1}{s^m} \qquad \text{. . . . . (2a)}$$

D 2

where T_1 is the time required for the first cycle of a batch (or sometimes the first product, e.g. an aircraft); T_s is the time required for the sth cycle of the batch (or sometimes the sth product); m is the exponent of the reduction ($0<m<1$); n is the magnitude of the batch, and T_{nc} is the cumulative average cycle time (or product time) over the sequence numbers 1 through n. The eqns. (1) and (2a), when plotted on log–log paper, appear to produce straight lines. Figure 1 shows eqns. (1) and (2) when the exponent of the reduction is $m=0{\cdot}32$, a value considered more or less normal. It corresponds with a 20 per cent fall in T_s for each doubling of s, or $T_{2s}=0{\cdot}8\ T_s$.

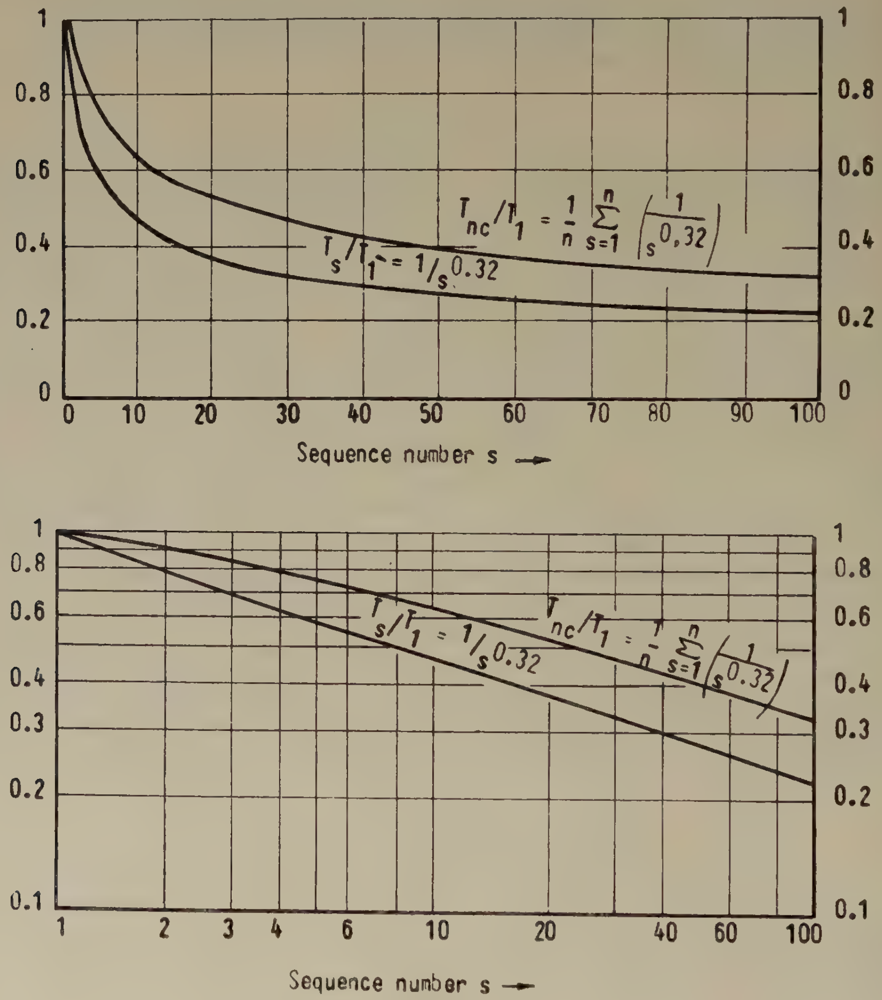

Figure 1. The gradual fall in T_s and T_{nc} according to eqns. (1) and (2).

Now, the question arises whether we may in actual fact expect a fall in T_s such as is indicated by these formulae. What light has experience to throw on the matter? First of all, it must be pointed out that the fall in time has to be analysed: there are two possible methods of going to work:

(*a*) when technical equipment and work organization remain steady, and

(*b*) when technical equipment and organization are gradually improved.

In the latter case, it does repeatedly happen that the fall in T_s is in accordance with formula (1) even over a relatively long period. Figure 2 gives an example of this. It concerns a joinery factory producing three types of wall elements for prefabricated housing for over a year. The reduction in this case is due to a combination of improved workshop organization, increasing skill, time rates and the perfecting of machinery and tools.

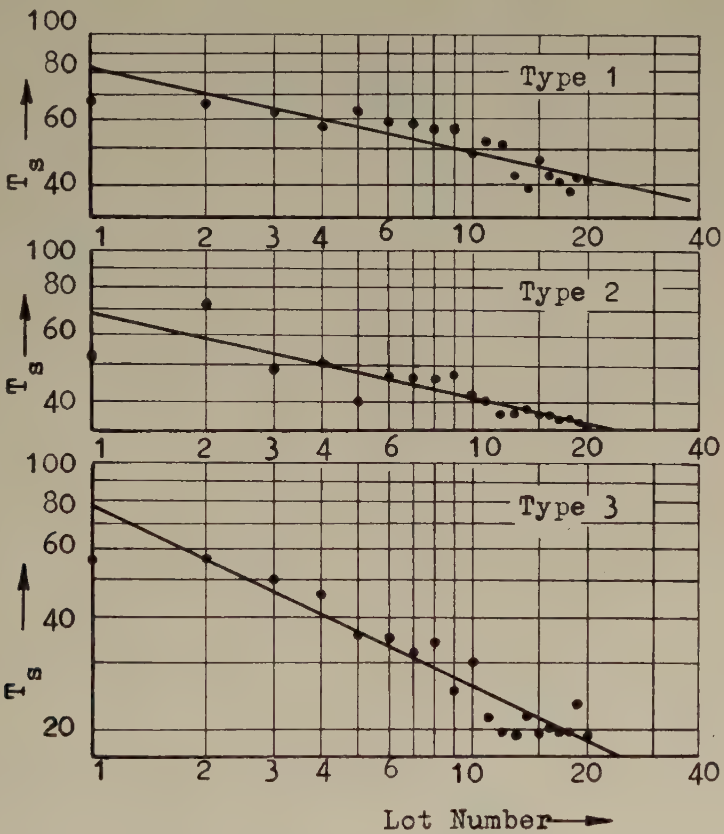

Figure 2. The fall in T_s per identical lot of elements for housing construction (14 months' continuous production).

On the other hand, if we examine the fall in T_s for cyclic work where no technical or organizational changes are made for a given task, it appears—as is only to be expected—that T_s tends to approach a certain limit value. Where relatively small numbers are concerned, this will not perhaps be immediately observable, but as the numbers grow larger, it becomes very obvious indeed. This point can be illustrated by the example of turret-lathe turning shown in Fig 3.

These and other curves of fall in T_s, appear to be satisfactorily explained

$$T_s = T_1\left(M + \frac{1-M}{s^m}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where M represents the 'factor of incompressibility'. $0 \leqslant M \leqslant 1$*. In the case of $M=0$, formula (3) reverts to formula (1). Figure 4 shows a set of curves for various values of M, for all of which, the exponent of reduction $m=0{\cdot}32$.

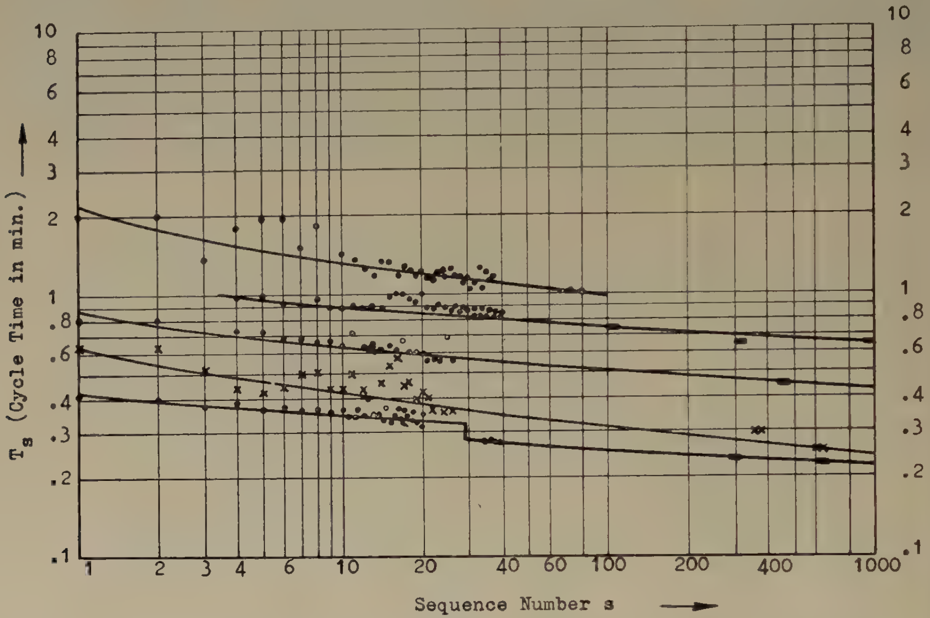

Figure 3. The fall in T_s (per cycle, excluding 'machine-times' affected by automatic feed) for a number of turret-lathe operations.

As regards the piece of work bearing the sequence number 'infinity,' it turns out that $T_\infty = MT_1$. One may therefore replace formula (3) with

$$T_s = T_\infty\left(1+\frac{1-M}{Ms^m}\right). \qquad (4)$$

Figure 5 now illustrates T_s/T_∞ for a number of values of M and for $m=0{\cdot}32$ (as in the preceding figure).

Throughout our observation of widely divergent operations, the course taken by T_s was found to be given quite satisfactorily by formulae (3) and (4), when a value of $m=0{\cdot}32$ was accepted for the exponent of reduction, and when a suitable value for M was chosen, dependent on the nature of the work. But M appears also to be dependent upon the commencing combination of skill and familiarity with the work in hand. It is not purely a summing-up of a number of machine-times—the times for manual operations per cycle will naturally fall gradually, but not to zero. They will tend to approach a certain limiting value. Analysis by means of cinematograph films assists in determining what it is that brings about this gradual reduction in the cycle-time T_s. Barnes and Perkins (see Barnes 1942) have shown, for example, that there

* The gradual fall in the compressible portion of T_1 (i.e. $(1-M)T_1$), may in addition to the exponent of reduction m, also be expressed as a percentage reduction at each doubling of s, this being referred to as the reduction factor f. Using (3), we find

$$1-\frac{f}{100}=\frac{(1-M)T_1/(2s)^m}{(1-M)T_1/s^m}=\frac{1}{2^m}, \text{ or } f=100\left(1-\frac{1}{2^m}\right).$$

As regards the expected values of m, $f \simeq 63\ m$.

is a decrease from cycle to cycle in the number of times the eyes have to be re-focused. Discontinuous and hesitant movements become smoother; fumbling disappears. Where the work is asymetric as regards left and right hands, we perceive continuous improvement in the concurrent performance of movements with the two hands.

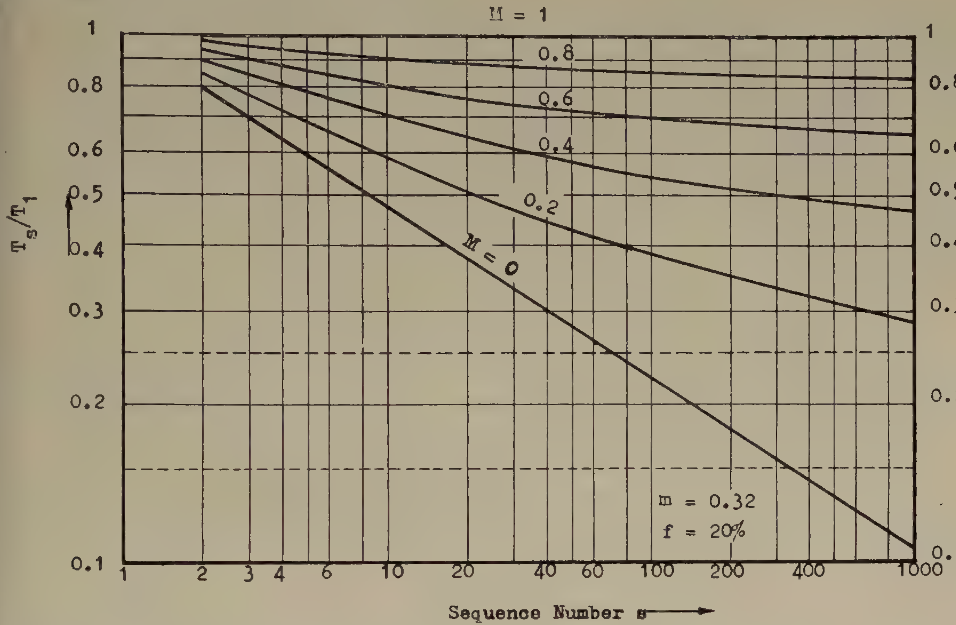

Figure 4. The fall in $T_s T_1$ according to formula (3) for various values of M, and for m=0·32.

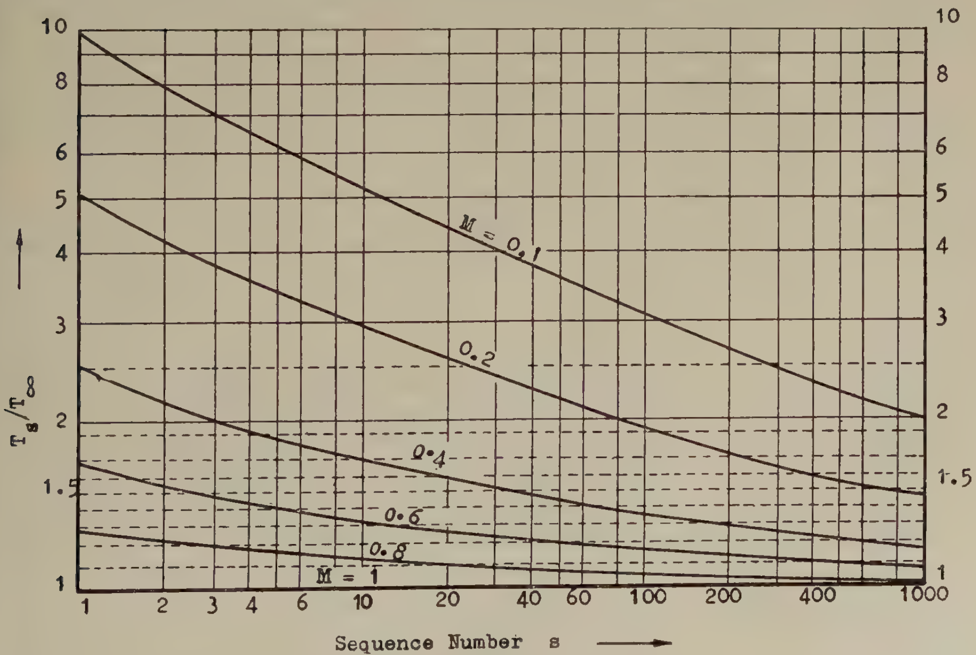

Figure 5. The fall in T_s/T_∞ according to formula (4), for a number of values of M and for m=0·32.

In examining assembly operations, where the exponent of reduction $m=0{\cdot}32$ (or $f=20$ per cent), we have repeatedly found a factor of incompressibility M of about 0·25. Figure 6 shows three examples from the metal-working and wood-working industries. As the operations in successive tasks increase in uniformity, the value of M is found to be greater. In turret-lathe operations, for instance, we have found $M=0{\cdot}5$ excluding automatic feed elements; when the latter are included, still higher values of M are found. In all the examples given up till now, m has been equal to 0·32. It seems possible that there may be cases where other values of m, dependent for example upon the duration of the cycle, might give better results, but we have not yet been able to discern any clear indication of it. At the same time, it ought to be pointed out that various combinations of m and M, can produce practically identical curves for T_s for quite strongly divergent values of s.

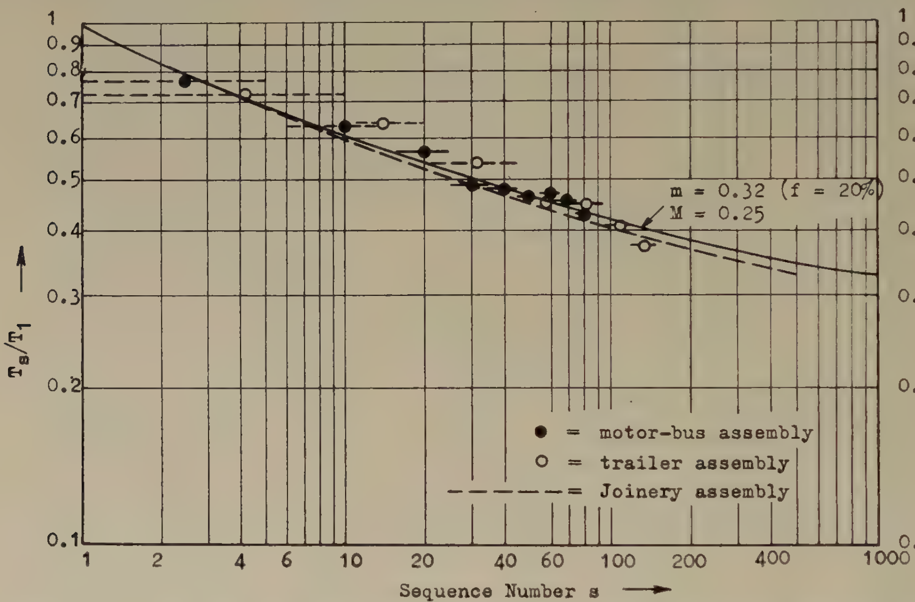

Figure 6. The fall in T_s for a number of assembly operations: motor-bus assembly, trailer assembly, and assembly of domestic joinery (92 cases).

§ 3. Applications to Batch-production Time-studies

Let us now go a little deeper into the matter from the point of view of the firm working on batch-production. The product is often as changeable as the weather, but most of the operatives are continually in charge of the same machine or carrying out the same manual process. In most cases the work to be done is cyclic. Often enough the operative is engaged on a number of jobs each week and sometimes several a day. A precisely similar task is hardly ever repeated by the same operative at any rate not within a number of months. In the course of time, usually after some years, the operatives come to attain a more or less stationary general level of skill for their type of work. Contrary to an often-expressed opinion, it appears in spite of this that there are a good many cases in which the time these experienced operatives require for a given work cycle falls gradually but considerably

within a job. Examples of this sort of fall in cycle time have been given in Figs. 3 and 6.

In fixing time-standards, we usually calculate the average time required for the cycles to be performed T_{nc}. Referring back to formula (3), we may write

$$T_{nc}=\frac{1}{n}\sum_{s=1}^{n}T_s=T_1\left[M+\frac{1-M}{n}\sum_{s=1}^{n}\left(\frac{1}{s^m}\right)\right] \quad . \quad . \quad . \quad . \quad . \quad (5)$$

T_{nc} is given in Fig. 7 for $m=0{\cdot}32$ and for incompressibilities $M=0{\cdot}25$ and $0{\cdot}5$. When the batch quantity n is not small, the following formulae apply:

$$T_n=T_1\left(M+\frac{1-M}{n^m}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$T_{nc}\simeq T_1\left\{M+(1-M)\left(\frac{1}{(1-m)n^m}-\frac{1}{n}+\frac{1}{2n^{1+m}}\right)\right\}\simeq T_1\left(M+\frac{1-M}{(1-m)n^m}\right). \quad (6)$$

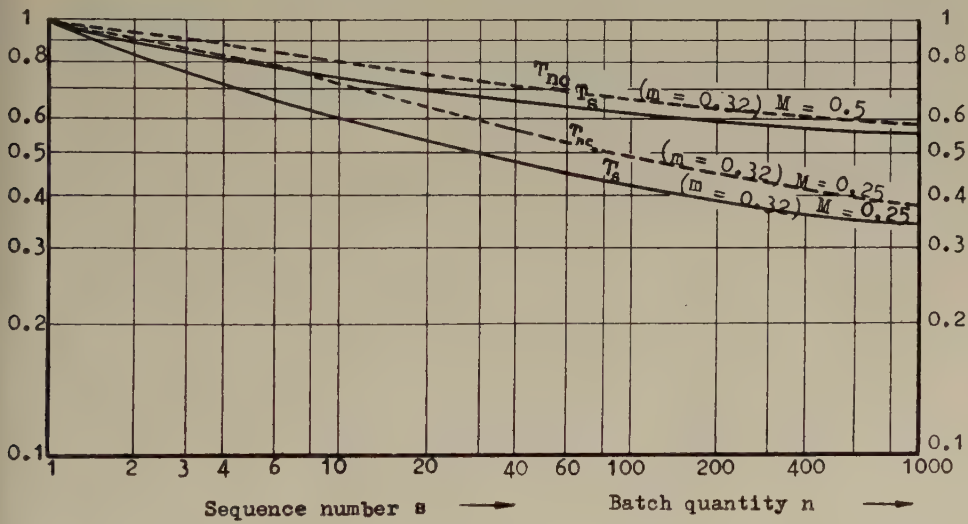

Figure 7. Plots for T_s and T_{nc} according to formulae (3) and (5), for an exponent of reduction $m=0{\cdot}32$ (i.e. $f=20$ per cent), and for incompressibility factors $M=$respectively $0{\cdot}25$ and $0{\cdot}5$.

If time studies are being made, it is important to know the sequence number n' of the cycle for which the time required $T_{n'}$ equals the value T_{nc} being sought. If we can be enabled to make our time studies at cycles round about sequence number n', it is clear that we will obtain the time T_{nc} we are looking for.

When the values of the exponent of reduction m are widely divergent (between $m=0{\cdot}1$ and $0{\cdot}4$), the following appears to apply:

$$n'/n\simeq 3. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

This is a general rule that applies in the case of all the formulae mentioned here, whatever the value of the incompressibility factor M. It is also true that n'/n is not highly dependent upon n, as is shown in Fig. 8. For instance,

it may be assumed that the average time required T_{600c} for a batch of 600 pieces could be obtained from time studies at about the 200th piece.

§ 4. Application to the Establishing of Production Time Standards with Elemental Time Values

Elemental time values are time standards for the 'elements' that are used for performing a given class of work. The data are used as a basis for determining time standards on work similar to that from which the data were obtained without making actual time studies.

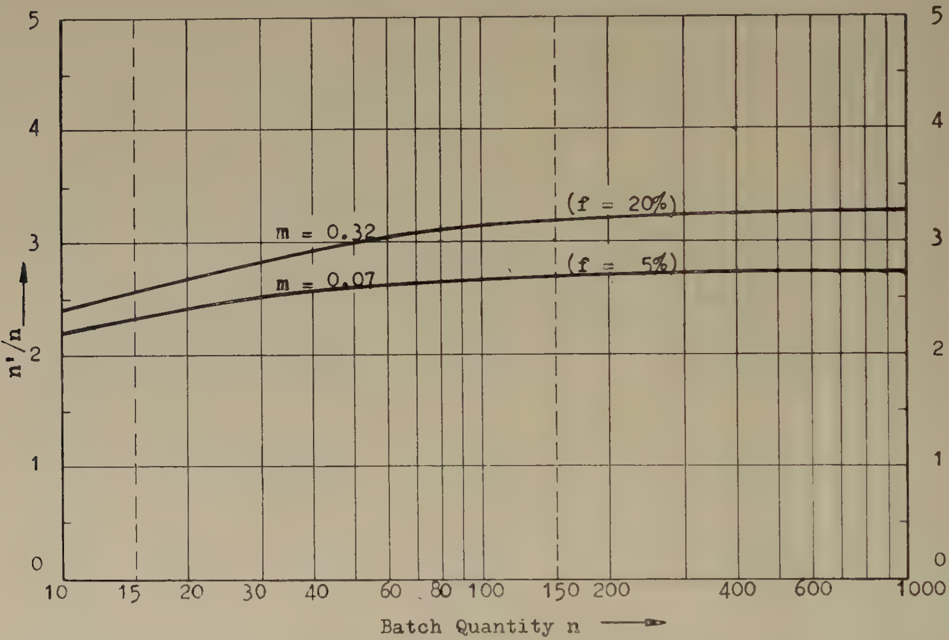

Figure 8. The relation between the batch quantity n and the sequence number n' for which $T_{nc} = T_{n'}$ ($m = 0{\cdot}32$ and $m = 0{\cdot}07$).

In deriving elemental time values, one may ensure that they will be accurate for the largest batch-quantity to be expected, by taking into account what has just been pointed out. In making use of these element times for the calculation of cycle times for smaller batches, it appears that a correction has to be applied to the result, otherwise the time rate will prove to be too low. The magnitude of this correction may be ascertained by making a number of time studies at highly divergent values of s. The results are then divided by the relevant cycle time according to the element times T_c and plotted graphically. Figure 9 gives an example.

To obtain a generally applicable norm for a certain type of work (for instance, a group of machines), one leaves out of account all the 'incompressible' machine-times, and similar elements. By comparison with a series of standard curves for divergent values of M, the applicable formula can be indicated, and we can compile a table such as the following with the assistance of the standard tables available. From the tables may now be read off the value,

expressed as a function of the batch quantity n, by which the computed cycle time has to be multiplied to obtain the time required.

Example: In the case of a batch of 250 pieces with 20 per cent automatic-feed machining times, the computed cycle time has to be multiplied by 1·1.

When the table compiled in this way is used in connection with a financial incentive scheme it may be desirable to assume that the cycle time T_s does not fall further after reaching a certain value of s.

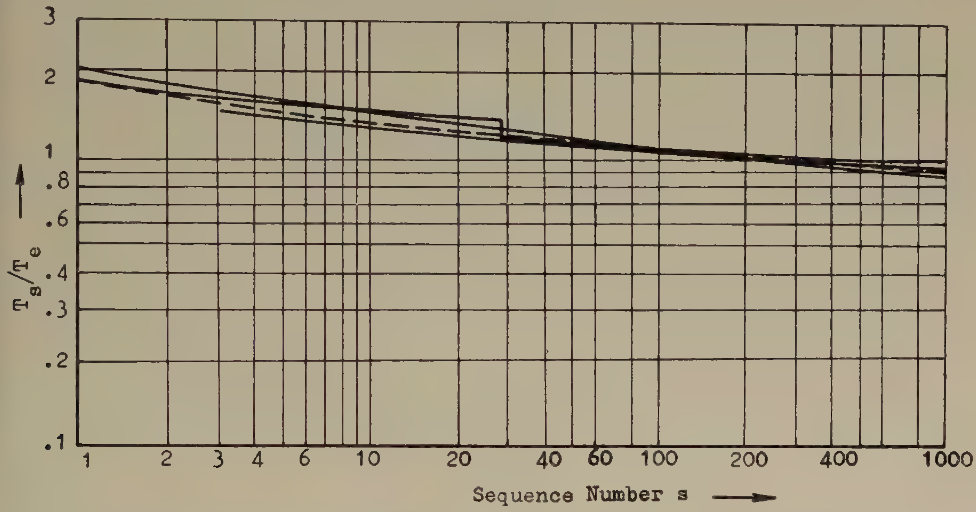

Figure 9. An example of collected data concerning turret-lathe turning.

No. of pieces n	Automatic-feed machining times (Percentage of cycle time) 0–10	11–30	31–50	51–70
	No. to be taken into account:			
8– 11	$n+4$	$n+3$	$n+2\frac{1}{2}$	$n+1\frac{1}{2}$
12– 17	1·35 n	1·3 n	1·2 n	1·15 n
18– 25	1·3 n	1·25 n	1·2 n	1·1 n
26– 40	1·25 n	1·2 n	1·15 n	1·1 n
41– 75	1·2 n	1·15 n	1·1 n	1·1 n
76– 150	1·15 n	1·1 n	1·1 n	1·05 n
151– 300	1·1 n	1·1 n	1·05 n	1·05 n
301– 550	1·05 n	1·05 n	1·05 n	n
551–2000	n	n	n	n

On a trouvé que, lorsqu'un cycle de travail est répété beaucoup de fois ou lorsqu'on produit un nombre d'exemples du même produit, le temps nécessaire par cycle ou par produit décroit progressivement durant de longues périodes, même en cas d'ouvriers habiles et possédant expérience. Ceci complique la fixation du temps-étalon pour le travail de production. On donne des formules permettant de tenir compte de la diminution du temps de cycle pendant le chronométrage et formant un abord quantitatif fondamental à l'évaluation de l'habileté due à l'éxperience.

Es wurde gefunden, dass, falls ein Arbeitszyklus mehrmals wiederholt wird oder falls eine grössere Anzahl von Mustern desselben Erzeugnisses hergestellt wird, die per Zyklus oder Erzeugnis erforderliche Zeit während sehr langer Perioden allmählich abnimmt, und zwar sogar im Falle geschulter und erfahrener Arbeiter. Diese Tatsache kompliziert die Festsetzung von Zeitnormen für Produktionsarbeit. Es werden Formeln aufgestellt, die es ermöglichen, während der Chronometrierstudien die Abnahme der Zykluszeit richtigerweise zu berücksichtigen; ausserdem schaffen diese Formeln einen grundlegenden quantitativen Weg zur Abschätzung der von der Erfahrung herrührender Gewandtheit.

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INTERMITTENT LIGHT STIMULATION AND FLICKER SENSATION

Some Studies on the Variability of Frequency of Intermittent Light Stimulus required for Constant Criteria of Flicker Discomfort

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Flicker sensation depends on the frequency of the intermittent light stimulus, but the frequency required for a given criterion of flicker sensation shows a marked variability for different occasions with the same observer, or for different observers.

This variability was studied using the multiple criterion technique, flicker judgments being obtained from twenty subjects on a number of occasions. In one set of experiments the whole visual field was stimulated, in another a field approximately $20° \times 30°$.

Four criteria of flicker sensation were employed including the customary criterion of ' just perceptible ' flicker.

The results showed that :

(*a*) Small changes in stimulus frequency cause large differences in the noticeability of flicker and in the sensation of discomfort caused by flicker.

(*b*) Large changes in stimulus frequency cause little change in the apparent frequency of flicker, which remains constant around 16 c.p.s.

(*c*) As stated above, sensitivity varies markedly both between subjects and between occasions.

§ 1. Introduction

The conditions under which an intermittent light stimulus is subjectively interpreted as being continuous have for long been of considerable interest in the study of vision. The frequency at which this occurs under given conditions is called Critical Fusion Frequency or C.F.F. and has been used extensively as a clinical test and as an indication of the state of the visual perception mechanism.

The dependence of the C.F.F. on brightness was discussed over half a century ago by Porter (1902) and later the C.F.F. for a source of small apparent size was related to adaptation level and position in the visual field by Lythgoe and Tansley (1929). The effects of the amount of area of the retina stmiulated intermittently have been more recently studied by Bouma (1939, 1941), while Segal (1940) and Eastman and Campbell (1952) have investigated the effects of more complicated wave-forms, and the latter have proposed a ' Flicker Index ' to enable them to be predicted.

This present investigation, however, was first contemplated because there was very little information on the effect of presenting a flickering stimulus covering the whole visual field, as would occur in a lighting installation. The relation between frequency and discomfort at frequencies below the C.F.F. had also not been studied in any detail.

Many previous workers have noticed the variability between subjects and between occasions, and Misiak (1951) has related the subject differences to age. These observations, however, have all been made with small flickering fields and the differences found have not been very great.

The investigation discussed here was a study by means of the Multiple Criterion Technique (Hopkinson 1950) of the variations occurring when a

number of subjects recorded a number of times under a standard set of conditions, the following four criteria of flicker sensation :

(*a*) The frequency required for flicker to be ‘ just perceptible ’.

(*b*) Just obvious flicker—easily perceptible although not uncomfortable, but considered just strong enough to be immediately obvious on entering a room.

(*c*) Just uncomfortable flicker—now very obvious, and just becoming uncomfortable.

(*d*) Just intolerable flicker—could just be no longer tolerated, or the desire to close the eyes become very strong.

The C.F.F. has generally been measured by other workers by increasing the frequency of the intermittent light until it appeared to the subject as a steady light. Except in the case of the experiments which were carried out to determine the effect of ‘ adaptation ’ or desensitization to flicker, in the present investigation the threshold was determined as the point at which a previously steady light was perceived as ‘ just perceptibly flickering ’ (the condition referred to throughout this paper as ‘ Frequency Decreasing ’). This procedure was adopted to avoid any such adaptation effects, and the threshold so obtained will not necessarily be at exactly the same frequency as the C.F.F. obtained by the other method. In view of the relatively large spread in individual readings, however, it has been considered feasible to assume in comparing the present work with that of other investigators that the two flicker thresholds are the same. All the results referred to in this paper were obtained by the method of decreasing frequency except where it is specifically stated otherwise.

§ 2. Subjective Descriptions of Flicker—Real and Apparent Flicker Frequency

The choice of words to describe the four basic criteria above was made as a result of pilot experiments in which the investigators themselves made judgments with varying degrees of flicker. Flicker was found to be a sensation which varied with frequency not only in amount, but in nature. The choice of criteria was therefore not simple. At the threshold of flicker sensation, a just perceptible disturbance of the field intensity was noticeable, chiefly in the periphery. This disturbance did not vary much in kind *or in apparent frequency* when the objective frequency of the intermittency was varied. The apparent frequency of flicker at the C.F.F. was always of the order of 16–20 c.p.s. even though the actual frequency was much greater (at high luminances) or lower (at low luminances). Bartley (1941) has recorded this result and attributed the phenomenon to the intrinsic discharge of the ganglion cells in the retina.

At a frequency slightly below the C.F.F., the whole field was observed to flicker, even though the greatest activity was still in the periphery. At this stage the apparent frequency appeared to remain the same as the frequency at C.F.F. (i.e. about 16 c.p.s.) but the flicker *discomfort* had increased. At a still lower frequency the discomfort became considerable, although the apparent frequency had barely changed, and the first reduction in apparent flicker

frequency was not observed until the sensation of flicker was intolerable. At this stage the field appeared to break up into rapidly moving patches of various configurations. Most observers reported sensations of coloured flashes, and a feeling of marked disorientation was general. At very low frequencies (i.e. about 4 to 6 c.p.s.) this feeling of disorientation disappeared, the discomfort became much less, and the apparent flicker frequency corresponded closely with the true frequency.

The four criteria used in these studies are, therefore, assessments of *flicker discomfort* and not of apparent flicker frequency, even though frequency is the physical variable which is being altered. Throughout the range covered by the four criteria, the apparent flicker frequency remains very closely constant.

Segal (1940) in his thesis has described exhaustively but only qualitatively the subjective effects which arise from intermittent light stimulation at frequencies well below the C.F.F. thresholds, and his description should be consulted.

§ 3. Experiments with a Sector and Limited Field

The subject looked through an aperture in a box at an illuminated screen of white card as shown in fig. 1, using both eyes. For the standard conditions of the control experiments, a field of view of approximately $20° \times 30°$ was illuminated to produce an average value of 50 ft lamberts. At a position 5° above the centre of the field of view, a slit was cut in the card screen and illuminated from behind with a frosted ‘ striplight ’ lamp. (The dimensions and luminance of this slit were such as to correspond to the location in the field of view of a 5 ft fluorescent lamp at a distance of 15 ft.) The luminance of this slit under the standard conditions was 5 candles/in.^{2}.

Figure 1. Restricted field flicker apparatus.

All the lamps operated on a d.c. supply, and the fluctuation in the stimulus was provided by a sector disc mounted immediately behind the aperture in the box, and therefore close to the eyes of the subject.

A chin rest was provided to locate the eyes opposite the centre of the aperture so that the line joining the subject’s two eyes passed through the axis of the sector disc. This disc had five dark segments of angular width 18°, thus giving

a light to dark ratio of three to one. It could be rotated by a small electric motor whose speed of rotation could be controlled by the subject himself. The speed of the disc was measured stroboscopically by the experimenter at the instant when the subject announced that it had been adjusted for the appropriate criterion of sensation.

The observations were made by 20 subjects. Each subject made observations six times under the standard conditions, and in addition, four subjects made observations over a period of about eight months to study the long term variations in subjective response. During the course of these experiments a small number of subjects made observations also under other conditions of field size and luminance. The results of all these experiments are discussed later.

The subject, having been previously adapted to normal daylight or artificial lighting levels of luminance involved in his ordinary work, was given a few minutes to adapt to the 50 ft lamberts of the visual field in the apparatus with the sector running to interrupt the field at a frequency well above that liable to cause perceptible flicker.

In preliminary experiments, the subject was instructed to fixate on a mark at the centre of the field, but it was found that this procedure tended to produce erratic results. Le Grand (1931) has shown that if rigid fixation is maintained the peripheral retina becomes less sensitive to flicker, and as it is not possible to maintain very accurate fixation for any length of time (certainly with inexperienced subjects), the frequency at which flicker first becomes apparent on the peripheral field tends to depend on the timing and extent of the involuntary excursions of the eye around the fixation point. In any case, fixation does not correspond with practical conditions in a lighting installation, and it was considered preferable to instruct the subject to search the area around the centre of the field with conscious eye movement, reduce the speed of the sector motor gradually, and to report, for the first criterion, the instant at which he was first aware of flickering sensation in some part of the visual field. The experimenter adjusted the stroboscope continuously to keep a pattern on the back of the sector disc rim stationary and noted the reading when the first criterion of sensation was reported. The subject then lowered the speed of the sector disc to achieve the other three criteria in turn. After the frequency for just intolerable flicker had been determined, the speed of the sector disc was lowered still further, and the subject instructed to raise it again until the sensation of flicker corresponded to that previously regarded as just intolerable, and then to raise it further until the sensation corresponding to the other three criteria were produced in turn. This procedure enabled the adaptation (or, more strictly, desensitization) effect to be studied.

The apparatus, while permitting stimulation of large amounts of the visual field than had been used by the majority of investigators hitherto, still did not permit the entire field of vision (amounting to about 5 steradians in subtense) to be stimulated with a fluctuating luminance.

Furthermore, with vision of a large field through a rotating sector disc, a finite distance in front of the pupil, there is a phase displacement between the stimulation of different parts of the retina. In fact only points on the retina lying on the same apparent radius of the sector disc will be stimulated in the same phase. (The effect can be compared with that of a focal plane shutter in

a camera). When binocular vision is used, since corresponding points on the two retinae will not (except those on the equator) lie on the same apparent radius, there will be a phase difference between their stimulation.

Experiments to assess the effect of phase difference in the case of binocular vision were carried out with four subjects, and it was found that increases of frequency varying from 0 per cent to 19 per cent, with an average of 8 per cent, were necessary for the same criteria of sensation when changing from monocular vision to binocular vision with the restricted field apparatus. This is a greater difference than that of 5 per cent found by Ireland (1950) for the difference between monocular and binocular vision fusion frequency when both eyes were stimulated in the same phase relationship, but approximately the same as that obtained by Perrin (1954). It was also found that halving the size of the opaque sectors in the disc and doubling their number gave entirely anomalous results, indicating that large phase-difference effects could become important.

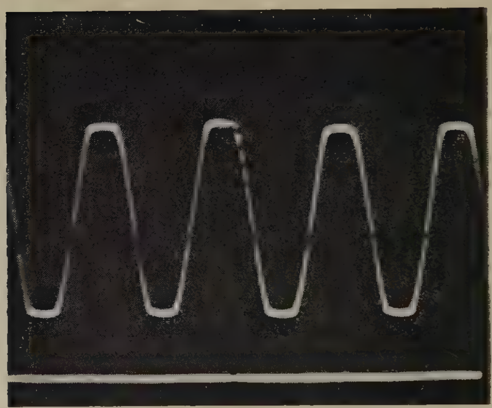
§ 4. Effect of Stimulating the Whole Visual Field

Both the above disadvantages were overcome by the development of an experimental arrangement which more nearly simulated a normal lighting installation with a fluctuating light-source. A 1 kw projector lamp (supplied with d.c.) was placed inside a slotted cylinder drum which could be rotated round the lamp. A second slotted cylinder was placed outside the first and held stationary. The rotation of the inner cylinder, at a speed which could be varied, provided a fluctuation of the light output of the apparatus which could be adjusted in frequency from zero up to over 150 cycles per second. The wave-form of the light fluctuation is illustrated in Fig. 2.

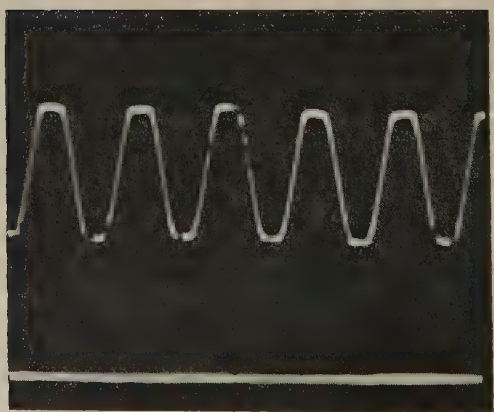
The general arrangement of the experiment is shown in Fig. 3. A cylindrical diffusing screen surrounded the fitting to give an approximately uniform illumination of the screen and the whitened walls of the room. The greatest average luminance of the visual field which could be obtained with this arrangement was 5 ft lamberts, owing to the inefficiency of the 'lighting fitting'.

The speed of rotation of the inner cylinder drum (and hence flicker frequency) was measured by means of a directly coupled tachometer generator connected to a rectifier voltmeter. The inertia of motor and drum were so great that in this experiment it was necessary for the experimenter to control their speed. There is, however, extensive evidence from subjective experiments in glare that no systematic error is introduced by experimenter-control as compared with subject control. The subjects entered the room adapted to ordinary working levels (sunlight being avoided) and were allowed to adapt for two minutes to the luminance level of the experiment. This level was provided by a non-fluctuating filament lamp. At the end of this time, the rotating cylinder drum was run up to a high speed, and the lamp inside it switched on to replace the steady source. The subject sat facing a screen, the fitting being out of his field of view, and he was instructed to search an area between two marks on the screen, at eye level and 10° apart horizontally, while the experimenter reduced the speed of the motor steadily (at an approximately constant rate of $\frac{1}{2}$-cycle per-second-per-second over the critical part of the frequency range). The subject was asked to report immediately the first signs of flickering at some point in the visual field were noticed. The speed

100 per cent modulation



75 per cent modulation



50 per cent modulation

Figure 2. Wave-form of light fluctuation from mechanical flicker source.

at which this occurred was noted, and the speed further reduced until the other three criteria had been reported in turn. The observations were then repeated as the speed was raised from a very low value, in the same way as described in the case of the restricted-field experiments.

Twenty subjects made observations, the majority being the same subjects as for the previous experiments with the smaller field. The objective was that each subject should also make six observations under the full field conditions, but this was only possible for about one third of the subjects. Another third made observations on five occasions, and the remaining third on four occasions.

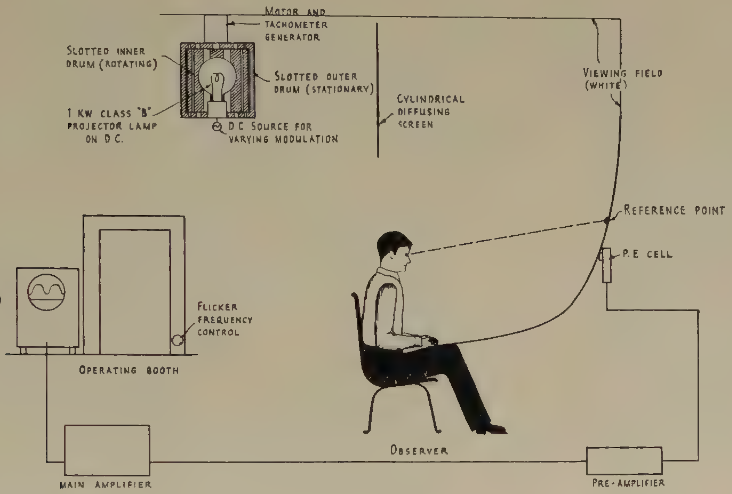


Figure 3. Experimental arrangement for flicker observations. (Full field experiment.)

§ 5. Variation of Subject Sensitivity

5.1. *Variation between Subjects*

Figure 4 shows the distribution of the judgments made for the two sets of conditions obtaining in the small field and in the full field experiment. In these histograms, the average frequency required by each subject for the four criteria of flicker sensation has been plotted. It will be seen that not only is there a wide spread of results (amounting to 20 cycles per second and more) but the criteria overlap so that at certain frequencies (for example 65 cycles per second in both experiments) some subjects were only just able to perceive a flicker which others complained was 'just intolerable'.

The distributions of frequencies obtained from the 20 subjects were not statistically 'normal', but there does not seem to be any reason why they should not be so if a large enough sample of the population were taken. Calculation of averages and standard deviations (S.D.) as if for a normal distribution gives the results shown in the Table (cols. 2 and 3). For the criterion of 'just perceptible', the coefficient of variation (S.D. as percentage of average) was approximately the same for the small field and full field experiments (7·4 per cent and 7·0 per cent respectively).

The variability was rather greater as the flicker discomfort increased, but was comparable in the two experiments.

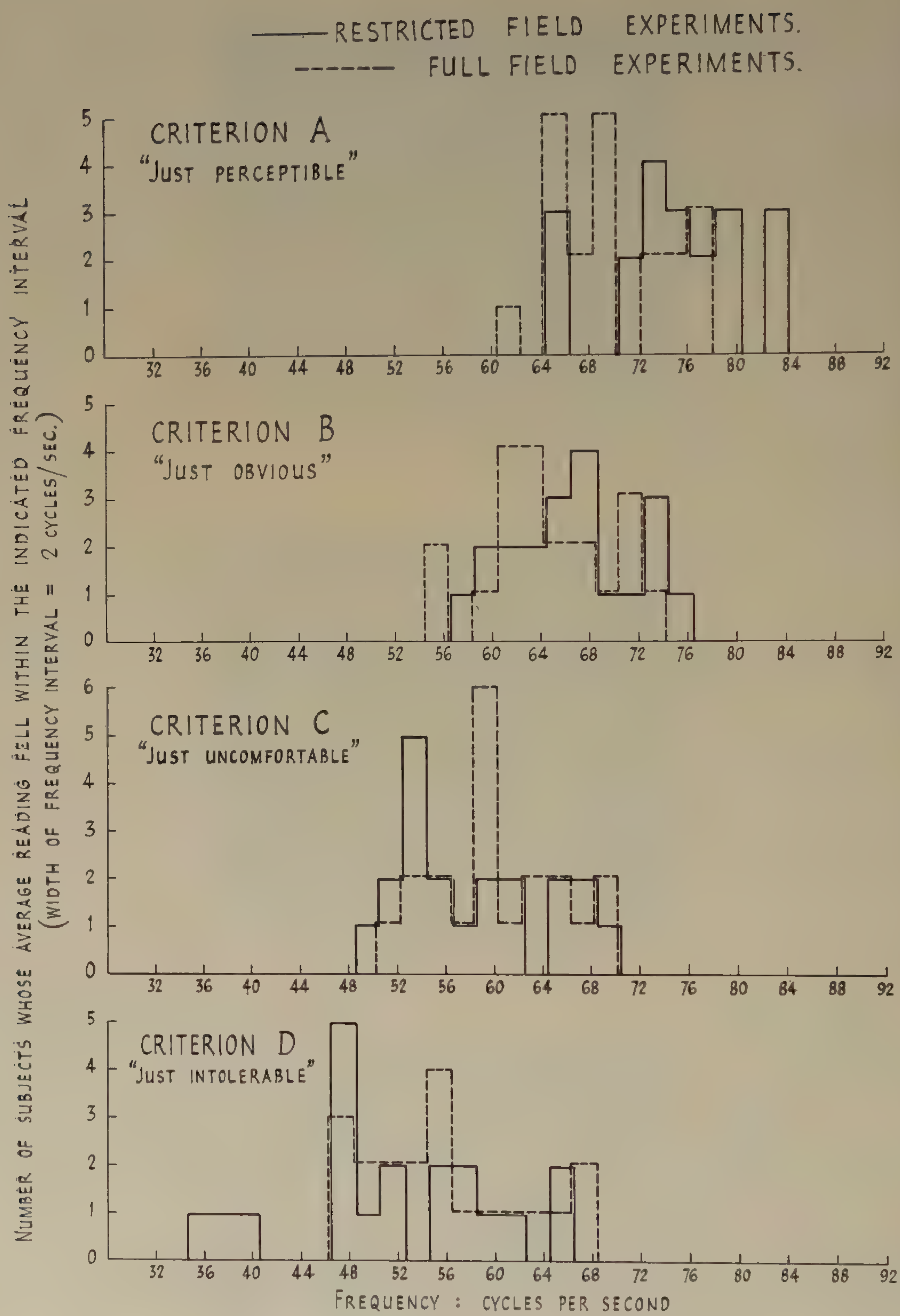


Figure 4. Distribution of average values of flicker frequency for 20 subjects, for four criteria of flicker sensation.

5.2. *Variation with Time*

The variability in sensitivity of one subject from one occasion to another is given by the judgments made by three subjects on the full field experiments over a period of eight months, and also by the smaller number of results given by the

remaining subjects over a rather shorter period. The first series showed that quite a high degree of consistency could be maintained over this period, and the standard deviations calculated from the 23 readings of each of the three subjects were 2, 2·5 and 2·4 cycles per second. The series of results shown in Fig. 5 is that for the second subject who showed the greatest variability of the three. A fourth subject, however, showed a much greater variation in frequency for 'just perceptible' flicker. Some of the other 16 subjects also showed a much greater variation than this, even in the smaller number of readings. The extent of the variation shown by the 20 subjects is indicated in the Table, columns 6–11.

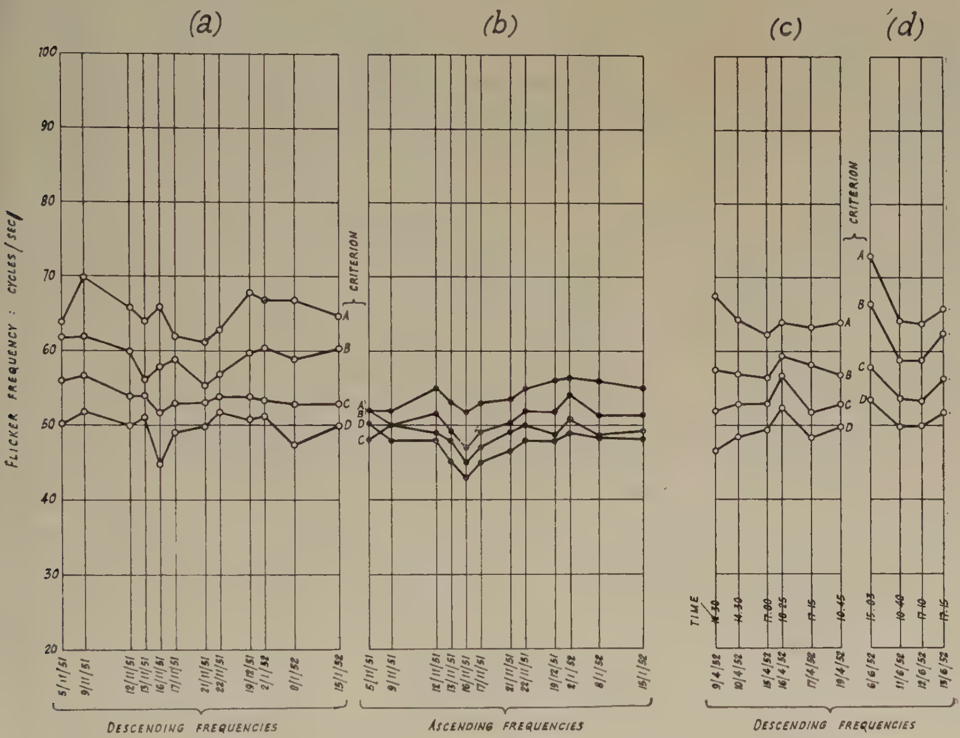


Figure 5. Variation of one subject on control experiment (P.P.). (Full field.)

Here the greatest frequency range shown by the readings of any subject, and the smallest range also, have been given, together with the average range which was covered by the readings of each subject, in terms of percentage of average frequency. It will be seen that there were considerable differences between the consistency of different subjects. For any of the criteria of flicker discomfort it was possible to find a subject whose sensitivity (as measured by his selection of frequency for the particular criterion of sensation) did not vary by more than a total of 7 per cent from his average value. On the other hand, some subjects gave results which covered a range amounting to a total of up to 60 per cent of their average frequency. Goldstone (1955) has found a high individual variability in some observers, which he correlates with a high anxiety level.

Results of Observations of Flicker Sensation made by 20 Subjects

	Criterion	Mean frequency for each criterion						Range of variation of subjects						Ratio— Rdgs. Freq. : Decreasing / Rdgs. Freq. : Increasing			Separation between each criterion and that following : log units					
		Freq. Decreasing			Freq. Increasing			Freq. Decreasing			Freq. Increasing						Freq. Decreasing			Freq. Increasing		
		c/s	Stnd. Dev.	Coefficient of Variation (%)	c/s	Stnd. Dev.	Coefficient of Variation (%)	Av. Range (%)	Smallest Range (%)	Largest Range (%)	Av. Range (%)	Smallest Range (%)	Largest Range (%)	Av. Value	Smallest Value	Largest Value	Av.	Smallest	Largest	Av.	Smallest	Largest
	Column 1	2	3	3 a	4	5	5 a	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Restricted Field Experiment (50 ft—1)	(*a*) Just Perceptible	75·1	5·6	7·4	64·3	9·8	15·2	19·4	8	42	14	6	30	1·17	1·05	1·38	0·054	0·013	0·10	—	—	—
	(*b*) Just Obvious	66·4	8·5	12·8	57·1	6·3	11·0	15	5	25	16	6	31	1·16	1·07	1·40	0·057	0·034	0·11	—	—	—
	(*c*) Just Uncomfortable	58·2	6·1	10·5	52·6	6·7	12·8	15	7	25	18	3	40	1·11	1·03	1·29	0·064	0·028	0·165	—	—	—
	(*d*) Just Intolerable	50·3	8·5	16·9	47·9	7·1	14·8	24	6	50	28	9	52	1·05	0·95	1·19						
All-round Visual Field Experiment (5 ft—1)	(*a*) Just Perceptible	70·1	4·6	7	60·1	6·3	10·6	12·1	2·6	59·6	9·6	3·9	19·8	1·17	1·04	1·35	0·033	0·012	0·079	0·033	0·012	0·065
	(*b*) Just Obvious	64·8	5·2	8	56·0	6·0	10·7	8·7	2·8	23·0	12·5	4·1	25·2	1·16	1·03	1·32	0·028	0·011	0·055	0·023	0·006	0·036
	(*c*) Just Uncomfortable	60·9	5·7	9·3	53·0	5·6	10·6	9·4	4·5	18·2	13·2	6·2	35·0	1·15	1·03	1·27	0·037	0·013	0·068	0·019	0·009	0·033
	(*d*) Just Intolerable	55·9	6·5	11·7	50·7	5·9	11·5	9·2	3·1	20·5	12·7	4·7	38·2	1·10	1·04	1·25						

In general the average range of variation of sensitivity was comparable for all four criteria of sensation, although there was a tendency in both experiments for the range of variation of frequency to be low for the 'just obvious' criterion, and in the full field experiments for the range to be less for the criterion 'just intolerable' than for 'just perceptible' flicker.

When observations were made with the frequency increasing, the variability for the criterion of 'just perceptible' flicker was greater between different subjects, but slightly less between the observations of a given subject from time to time.

The variability of response which has been found in the present investigation is much greater than has been reported by previous investigators. It is thought probable that the smaller sizes of visual field used by these previous investigators were conducive to greater consistency in the results. Again, the pre-history of adaptation might have influenced the variability. It is believed that the time given to the subjects to adapt to the ambient luminance was fully adequate, but it is possible that a much longer adapting time might have reduced the variability.

Of the other factors contributing to variability in C.F.F., that of visual fatigue has been discussed by Zaccaria and Bitterman (1952) and by Ryan *et al.* (1953). Although experiments were conducted to study the effect of prolonged visual work on the C.F.F., as part of the present investigation, only in one case was it possible to associate changes in fusion frequency with visual work. The factor of age has been discussed by Misiak (1951). The subjects in the present studies were all in the 20–40 age group, and under the conditions of his experiments, Misiak showed that the variation between the limits of this group were only 5–8 per cent, so that the present experiments could not be expected to show any significant variations with age.

§ 6. The Relation between Frequency and Sensation

As stated above, one of the objects of the investigation was to obtain a relation between degree of flicker sensation and characteristics of the stimulus pattern. This was obtained by means of the multiple criterion technique, which while not aiming to provide a scale of sensation, enables changes in the stimulus characteristics to be assessed in terms of their subjective effect.

It has already been noted (§ 2) that the subjective changes which resulted from alterations in the frequency of the stimulus were changes of flicker discomfort or perceptibility. Apparent flicker frequency remained almost constant over a wide range of stimulus.

In both the restricted field and full field experiments, the frequencies selected for the four criteria of sensation by the 20 subjects on a number of occasions, as described above, are shown in the Table, columns 2 and 4. In columns 15 and 18 are shown the average frequency changes in log units corresponding to each step in flicker sensation. It will be noted that the four criteria were fairly evenly spaced for decreasing frequency; the average separation in the restricted field experiment being 8–9 cycles per second (0·06 log units or about 15 per cent) and in the full field experiment 4–5 cycles per second (0·033 log units or about 8 per cent). The 'sensitivity' or change in frequency to produce a given change in sensation was therefore nearly twice as great in the case of the full field experiment. It seems probable that,

of the difference in character of stimulation between the two experiments, the increase of field size to include the whole of the visual field was the one most likely to make this difference in sensitivity.

The relatively small change in frequency necessary when stimulating the whole visual field, to produce a large change in flicker sensation, is a feature of great practical interest. It will be seen that in the full field experiments there was found to be a difference of only 14 cycles per second (that is between 70 c.p.s. and 56 c.p.s.) on the average, between the frequency for 'just perceptible' flicker and 'just intolerable' flicker. This result is relevant in many ways to the problem of discharge lamp lighting on a.c. supplies and may explain, for example, why complaints of flicker are more persistant in this country with its 50 c.p.s. standard of a.c. supply as compared with the United States of America with its standard of 60 cycles per second. Recently the attention of the authors has been drawn to the even more marked complaints of people working in a large organization with a private a.c. supply of 40 c.p.s. frequency. Such a difference (20 per cent in frequency) can, under the appropriate conditions, make all the difference between a flicker that is uncomfortable and a flicker that is just beyond the range of perceptibility.

It is interesting to compare the present results with some observations of Engstrom (1953) on flicker sensations above the threshold of perceptibility. For various conditions of test field illumination (from 0·5 to 20 ft candles on a field $9{\cdot}5^\circ \times 12{\cdot}7^\circ$) and with light/time ratios of 0·028 to 0·97, giving values of 'just noticeable flickers' from 18 to 85 cycles/sec (average results for 4 subjects), he found that the frequency for 'disagreeably objectionable flicker' was a fairly constant value of 10 to 15 cycles/sec lower than these values in each case.

This criterion might be assumed to correspond to that in the present investigation, termed 'just uncomfortable flicker' for which was found to be required a frequency of 9·2 cycles/sec lower than for the criterion of 'just perceptible flicker' in the full field study, and a frequency of 16·9 cycles/sec lower in the restricted field study. (In further experiments with smaller field sizes, a corresponding difference of 20 cycles/sec was found at a field size of $10^\circ \times 10^\circ$.)

A further experiment of Engstrom's with a cathode ray tube screen confirmed this constant difference in frequency and also gave the position of a third sensation, 'noticeable but satisfactory flicker', occurring at 3–4 cycles/sec lower than 'just noticeable flicker'. This sensation might be interpreted as slightly less obtrusive than 'just obvious flicker' which in the present investigation occurred at about 5 cycles/sec lower frequency than 'just perceptible flicker' in the full field study and 10 cycles/sec lower frequency in the restricted field study.

It will be seen, therefore, that although the present results do not show the same consistency of separation of criteria as those of Engstrom, there is agreement on the order of the difference, and confirmation of the critical relation between frequency and sensation.

§ 7. Adaptation to Flicker

The extent to which a subject becomes desensitized to flicker by subjection to a strong flicker stimulus is indicated by comparing the sets of results obtained with frequency decreasing (col. 2 in the table) with those obtained with

frequency increasing (col. 4). Column 12 in the table gives the ratio between the two sets of results, and it will be seen that the frequencies required for the same criteria of sensation were on the average 5 per cent to 17 per cent higher when the frequency was being reduced than when it was being increased. In other words, after subjection to flickering light stimulus at low frequencies, the subject was desensitized so that the sensation of flicker discomfort was less than it was before the experience. The effect, as might be expected, was least at the low frequencies required for ‘ just intolerable ’ flicker, but the flickering sensation finally began to disappear (in both experiments) at a frequency 17 per cent lower than that at which it could first be seen when the frequency was reduced from a high value.

The effect varied with different subjects. The subject most affected showed a difference of 40 per cent in the restricted field experiment, whereas the subject least affected showed differences which were not much greater than the variability expected from the results.

Other investigators have noted this adaptation, or more properly ‘ desensitization ’ effect, and it has been established that its magnitude increases with angular distance on the retina of the stimulus from the fovea. Snell (1953) has found a drop of 25 per cent in sensitivity to flicker after half an hour with a 4° field, but only about half this drop with a 1° field for the same subject. Le Grand (1931) has described how, if the eye is kept accurately fixated, flicker in a peripheral field can disappear after a short time, only to reappear immediately the eye makes the slightest movement.

During the present investigation, confirmation was obtained of Snell's observation that subjection to intermittent stimulation at frequencies above those for flicker to be perceptible does not cause any desensitization. Snell also (from apparently very scanty data) states that when flicker is visible, its desensitizing effect appears to be independent of its frequency. No observations confirm this in the present study, in fact it was found that flicker at levels of sensation only a little greater than ‘ just perceptible ’ did not have any appreciable effect on flicker sensitivity.

In view of this desensitization effect, it would be expected that results obtained by other investigators for critical fusion frequency, by increasing the frequency until flicker just disappeared, would be lower than those obtained by reducing the frequency until flicker could just be perceived. It might also be thought that the former results would vary according to the frequency presented to the subject at the commencement of the observations. Snell's observations, however, seem to refute this, and in view of the fact that previous investigators have generally used small visual fields, it is probable that adaptation effects have not seriously affected their results.

The main influence of the phenomenon of desensitization on the present investigation was to protract the experimental part of the investigation, since only one set of observations could be made at one sitting, as it seemed wise to allow an hour or more to elapse between sets of observations by any one subject.

§ 8. Conclusions

It is evident from the experimental data that there will be a wide variation among a sample of the population in the responses to conditions of fluctuation of a light stimulus affecting the whole field of vision within the critical range. In

order to predict the incidence of complaints of flicker from a lighting installation it is necessary to consider the subject and the occasion of encountering the installation as independent entities. This gives rise to the concept of ‘ observer-occasions ’ in connection with the probabilities discussed below.

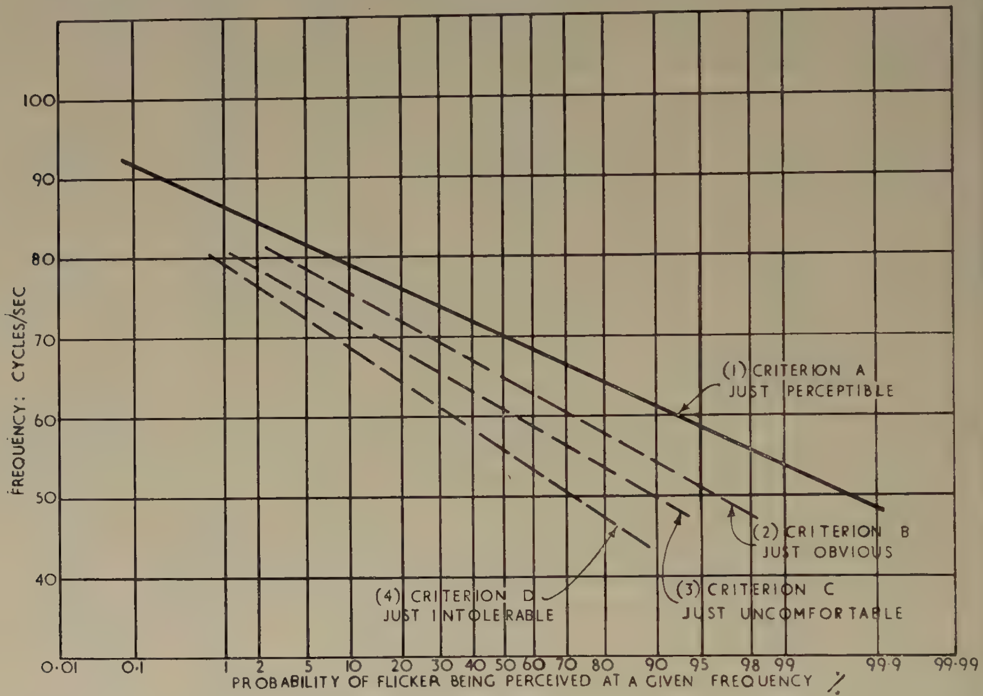


Figure 6. Relation between flicker frequency and probablilty of perception for conditions of full field experiment.

The standard deviation of the 100 readings of frequency for ‘ just perceptible ’ flicker obtained from the full field experiment may be used to obtain a probability curve for the whole population, of which the 20 subjects are considered to form a representative sample. The form of this curve is shown in Fig. 6 (curve 1). From this curve it will be seen that for the conditions of the experiment, where 70 cycles per second is the average frequency needed for flicker to be just perceptible, and is assumed to be the median value, a fluctuation frequency of 79 cycles per second would be perceptible on 10 per cent of all ‘ observer-occasions ’, a frequency of 61 on 90 per cent, and a frequency of 86·5 on 1 per cent of all observer-occasions. It does not follow of course that, at 79 cycles per second for instance, 10 per cent of observers will perceive flicker on all occasions or that all observers will perceive flicker on 10 per cent of all occasions. The more sensitive observers will perceive flicker on most occasions and the less sensitive ones on few occasions, and over a period of time when many observers have experienced the installation several times, the total number of occasions when some observers have reported that they are aware of the flickering would be expected to be 10 per cent of the whole sum of occasions on which an observer has experienced the installation.

The experimental results have also shown the critical effect of frequency on the flicker sensation produced, so that the range covered by the observations of

frequency for a given sensation can be shown to correspond to a large range of sensation among different observers subjected to the same conditions of flicker stimulation. As an example, the corresponding probability curves for the other criteria have been plotted in Fig. 6. These lines are not parallel to the one for criterion A, since the variance found experimentally increased for the stronger sensations of flicker. (Their slopes have been calculated approximately from the relation between the Standard Deviations of the subjects' averages.)

For the conditions of the full-field experiment, at a frequency of, for example, 70 cycles per second, on 50 per cent of the observer-occasions flicker will not be perceptible, and on the other 50 per cent it will be perceptible. This latter 50 per cent of observer-occasions will include 27 per cent on which flicker is said to be just obvious or worse, 15 per cent on which flicker is said to be just uncomfortable or worse, and 8 per cent on which flicker is said to be just intolerable or worse.

Consideration of the effect of adaptation to flicker shows that although the threshold frequency can be lowered appreciably by subjection to strong flicker stimulation, the effect of frequencies causing mild sensation is not so large. An observer encountering a lighting installation which he just perceives to be flickering is not likely therefore to suffer enough desensitization so that after some time he can no longer perceive it flickering, under conditions of normal seeing where the gaze is not fixed steadily on one point.

The use of the data obtained in this investigation to predict the degree of complaint likely to be received about a lighting installation in practice involves consideration of the wave-form of the fluctuating light stimulus, and the effect of wave-form and other stimulus characteristics on the sensitivity to flicker. These matters are discussed in other communications (Collins 1956 a, b).

The work described in this paper formed part of the research programme of the Building Research Station, and was undertaken under the aegis of the Joint Committee on Lighting and Vision of the Medical Research Council and the Building Research Board. The paper is published by permission of the Director of Building Research.

La sensation de papillotement dépend de la fréquence du stimulant intermittent de lumière ; cependant la fréquence nécessaire pour un critère donné de la sensation de papillotement montre une variabilité prononcée pour des cas différents avec le même observateur ou pour des observateurs différents.

On a étudié cette variabilité en employant la technique du critère multiple, les discernements étant obtenus des vingt sujets pour un nombre de cas. Dans une série d'expériences, le champs visuel entier était stimulé, tandis que dans l'autre série le champs stimulé était de $20^\circ \times 30^\circ$ environ.

On a employé quatre critères de sensation de papillotement, y compris le critère habituel de papillotement ' à peine perceptible '.

Les résultats ont montré que :

1° de petits changements de la fréquence du stimulant causent de grandes différences dans la perceptibilité du papillotement et dans la sensation de gêne, causée par le papillotement ;

2° de grands changements de la fréquence du stimulant causent un petit changement dans la fréquence apparente du papillotement, qui demeure constante à 16 c/s environ ;

3° ainsi qu'il est dit plus haut, la sensibilité varie d'une manière prononcée d'un sujet ou d'un cas à l'autre.

Die Flackerempfindung hängt von der Frequenz des intermittierenden Lichtreizes ab, doch zeigt die für ein bestimmtes Kriterium der Frackerempfindung benötigte Frequenz eine deutliche Veränderlichkeit für verschiedene Fälle mit demselben Beobachter oder für verschiedene Beobachter.

Diese Veränderlichkeit wurde mittels der 'multiple-criterion'-Technik untersucht, wobei die Flackerurteile von zwanzig Subjekten (mehrere Male von jedem Subjekt) erhalten wurden. In einer Experimentreihe wurde das gesamte Gesichtsfeld, in einer Anderen ein Feld von ungefähr $20° \times 30°$ stimuliert.

Einschliesslich des üblichen Kriteriums des 'gerade noch wahrnehmbaren' Flackers wurden im ganzen vier Flackerempfindungskriteria benutzt.

Die Ergebnisse zeigten, dass :

(*a*) kleine Veränderungen der Reizfrequenz rufen grosse Unterschiede in der Flackerwahrnehmbarkeit sowie in der Empfindung des durch den Flacker verursachten Unbehagens hrevor ;

(*b*) grosse Reizfrequenzveränderungen rufen einen kleinen Unterschied in der scheinbaren Flackerfrequenz hervor, welche einen konstanten Wert von ungefähr 16 Hz beibehält ;

(*c*) wie oben erwähnt, ändert sich die Enpfindlichkeit merklich sowohl von einem Subjekten zu einem Anderen als auch von einem Fall zu einem Anderen.

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CONSIDERATION OF THE USER IN TELEPHONE RESEARCH

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Some general points of method in determining the preferences of users for new technical devices are illustrated with example sobtained in the course of telephone-user research.

Formal preference research among telephone users is aimed at developing methods for determining future user wants. The broad objective is to assist in guiding technical research in directions that will support development and application. From this standpoint technical research is interested in two kinds of situations :

1. What the user thinks of a device (or system or service) he has been using. A human being (user) has been using a machine (device, system, service) in a certain environment for some time. We must be able to examine his experience with it so as to visualize a better machine.

2. Whether, if this new machine were built, the user will prefer it to the old when he actually comes to use it.

Underlying both these situations is a need for two types of techniques :

(i) Ways to give users the kind of experience with devices which will be informative for technical research.

(ii) Ways to extract preference design information from this experience.

When the user already has extensive experience with a device, the problem is how to find out which design features should be changed and which retained in a better device. The two common methods are : firstly, by approaching the user directly and questioning him regarding his opinions ; secondly, by observing his use of the device.

With a new device, there is the additional problem of how to provide the user with the right kind of experience with the new device before polling or observing him. To do this we may either build the new device or, where desirable and feasible, simulate it.

The rest of this paper is concerned with some of our research experience in polling, observation, and simulation.

§ 1. Methods for Investigating Preference

1.1. *When the Device is Available for Trial*

Let us consider first the case where the user has had sufficient experience with a device so that he has a stable attitude towards it. We are interested in collecting and evaluating this experience as a guide to redesigning a new device. Most commonly this is accomplished through polling, that is by questioning the user regarding his reaction to the device.

Polling is, of course, very widely used in industry. As a measure of user *opinion*, its usefulness has been amply demonstrated. Methods for bypassing its pitfalls are well known. As a guide to technical *design* of machines, however, we have had less success in getting by with polls. Questionnaires seem to provide reliable expression of overall preference reaction to a device, but they tend to be inaccurate and incomplete in providing detailed information as to just how the user uses the device and feels about it. This detailed information is essential for redesign.

One reason for inaccuracy and incompleteness of this information is that questionnaires rely on the user's memory and his memory is not good for details. He remembers much better what he has not liked about the device than what he has liked. Furthermore, he often has a distorted view of the way he himself actually uses the device. We found, for example, in one experiment, that most people think they use the telephone two to five times as often as they really do. Many users assume they hold the telephone receiver with their right hand, when in fact they use the left. In one survey about 80 per cent of a group of 300 users in our Laboratories recalled that the numbers on their telephone dial were black and the letters red ; actually the reverse is true.

Results of this sort have led us to two conclusions :

1. *For purposes of technical design, a poll must evaluate all of a particular user's relevant experience*, not just what he recalls at a particular time or what he selects as appropriate answers to your questions. To this end we have used what might be called *a 'feedback type of questionnaire*. It is a two-stage affair. First, each individual user in the group is polled on his experience with a device by means of a very general open-ended questionnaire. At some later time, the answers from all the users in the group are listed together in a random order, and each user is asked to indicate which are most important to him. For example, in one experiment, 10 users were asked : " What things annoy you about your telephone ? " Subsequently, they were presented with the complete list of 39 annoyances gathered this way and asked : " Which 10 annoyances would you most like to have removed ? " The results are shown in Fig. 1. The middle area represents annoyances which were important both before and after feedback. The top area, called errors of commission, were annoyances mentioned before but not after feedback. The bottom area, errors of omission, were annoyances mentioned after but not before feedback. It should be noted that the data come completely from the experience of the users themselves. *A priori* thoughts of the experimenter are not allowed to colour the results. This is as it should be ; we are interested in what the user's experience with the device actually was, not what the experimenter thought it should be.

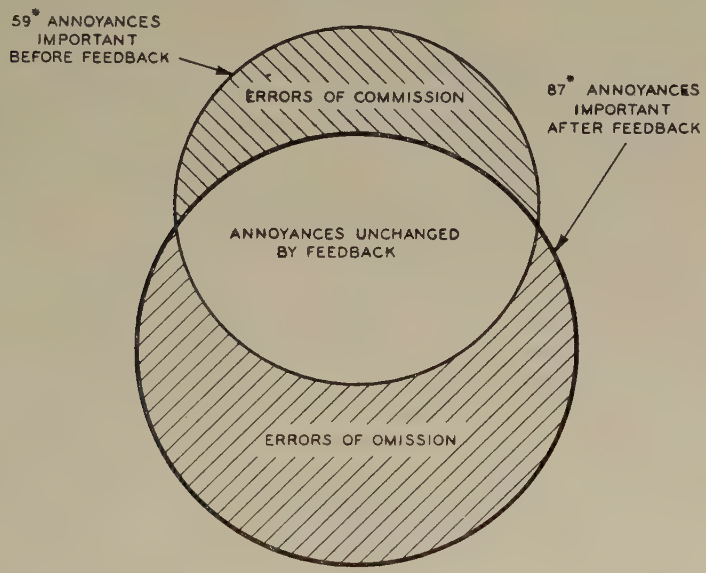
2. *In general, any poll or questionnaire may not by itself provide enough information for best redesign of the device.* The polling information may have to be supplemented by *objective observation* of the user's behaviour with the device.

We have found observation a very useful and necessary adjunct to questioning the user, and for some purposes, it has several advantages over polling. It removes the possibility of the interviewer's questions or personality influencing the user ; the data can often be obtained without the user knowing

he is being studied ; and his behaviour therefore does not assume the artificiality of the human quinea-pig in the laboratory.

In fact, a good deal of the information required for technical redesign can be obtained without any verbal contact with the user whatsoever. Physical measurements on the telephone circuits tell us, for example, whether or not the user dialed a seven digit number from memory ; if the number was not memorized, there will be a characteristic delay between the first three digits and the next four. In one experiment, 40 users were given a device which attached to the telephone handle in such a way as to permit the telephone to be wedged between the ear and shoulder, thus permitting a talker to keep both hands free during conversation. Preference for such a device was easily determined by inspecting the telephones periodically and noting how many devices were still being used.

ANNOYANCES MENTIONED BY TEN USERS



* THE NUMBER OF *DIFFERENT* TECHNICAL DIFFICULTIES IS MUCH SMALLER THAN THESE NUMBERS ; TWO ANNOYANCES MENTIONED BY TWO USERS MAY REFER TO THE SAME DIFFICULTY.

Figure 1.

One feature of user preference which can be studied particularly advantageously through observation, is the user's sensitivity to changes in his device. In various experiments we have made systematic changes in the user's telephone instrument and service without his knowledge. The general finding is that he is unaware of much larger changes than would be predicted from the conventional sensory differential thresholds measured in the laboratory. These unconscious ' thresholds are perhaps of enough interest to industry to warrant more study than they have received in the past.

Our feeling is that observation offers considerable promise as a measurement technique in preference. It can make use of the large numbers of personnel

working in an industrial organization. Data are thereby collected rapidly and economically. Measuring user reaction to changes in devices in the normal working environment by-passes many worries about the artificiality of laboratory tests. Such techniques as remote observation of user behaviour by means of inconspicuous television cameras are now being explored to supplement personal observation.

It would seem that observation and polling could often, with advantage, be used together.

1.2. *When the Device is Not Available for Trial*

Let us consider now the second type of preference problem. Will the user prefer a new device that is being contemplated ? If he would, what form should the device take to bring about the greatest gain in preference ?

In many cases the decision whether or not to proceed with research and development on such a device is based either on the best guess of expert technicians and market researchers or on the results of a poll of the potential users. The mistakes which can be made by these two methods are now so well known that they do not need amplification here. One recalls for example the insurmountable obstacles predicted for acceptance of the radio loudspeaker, the horseless carriage, the telephone, the safety razor, talking movies and television. Modern industrial research is based more and more on the belief that preference opinion without actual experience is unsound. We share this belief, and this viewpoint has led us in recent years to intensive research in *simulation* as our principal basis for predicting preference.

By simulation we mean providing the user with actual experience with the device without having to build it first or even knowing how to build it. This is, of course, accomplished by providing him with a substitute device in such a way that he perceives it as essentially the real device. Sometimes such subjective equivalence is almost perfect. Sometimes it is more approximate. Occasionally it is impossible. In the case of the telephone we are fortunate in the opportunities for successful simulation : what the user perceives about the telephone system is restricted to the instrument itself, what he can see of it, how he hears with it, and how it feels. All the rest is unknown to him and is simply a black box as far as he is concerned. We can achieve an effect at the user's end through a variety of changes in the black box. Thus, through simulation we can test many types of future telephone arrangements.

An example arose some years ago in the course of research on selective voice control. Would it be worthwhile to conduct research to learn how to build a voice translator which would convert spoken numbers into on-off dialing pulses suitable for operating telephone switches ? This technical problem raised some important user preference questions. If a voice translator were available, would telephone users prefer to dial numbers by voice rather than by finger ? How would they feel about talking to a machine ? Would this rule out users with speech impediments like stuttering ? The cost of the technical research programme would be so high that we would prefer to go into it with some assurance of favourable answers to the user preference questions.

Through simulation such questions could be answered well enough for an insignificant fraction of the effort that would have been necessary to build

the actual equipment. Figure 2 shows the simulation arrangement. Before starting the test, users were given operating instructions. If, at this time, any questions were raised about how the voice dialing was accomplished, they were answered frankly. They were told that human operators performed some of the machine functions, but that the privacy of their conversation was not affected.

The caller picked up his telephone, waited for a warning tone to stop, spoke the number he was calling, heard the ring, and started to talk when the ring was answered. As far as the user was concerned he was voice dialing. Actually, a silent operator heard the number he called and connected him to the called party. The instructions given to the operator to perform her job were identical with the rules of operation for the future voice dialing machine. The operator followed the rules rigidly. She was not allowed to use her intelligence to cope with situations the future machine was not intended to handle. By varying the rules for the operator more or less complicated machines could be preference tested.

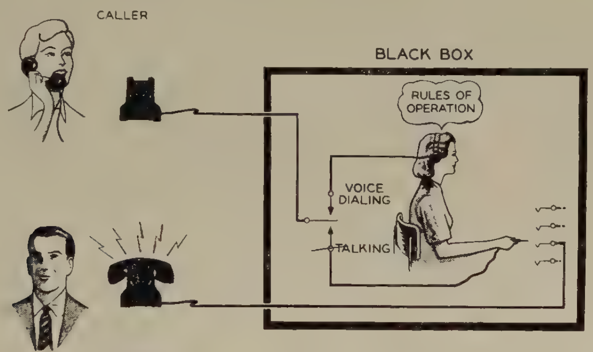


Figure 2.

People in the Laboratories who normally dial by finger used this voice dialing system for some months until it had become second nature to them and they no longer were conscious of participating in an experiment. Actually they alternated between voice and finger dialing at weekly intervals. During this period their dialing behaviour could be observed by physical measurements on the telephone circuits. Finally when their attitude towards voice dialing had become stable they were questioned regarding their preference between voice and finger dialing.

Some of the results may be of general interest in pointing up the productivity of simulation experiments. Polling the users before the experiment showed that most of them expected to prefer finger dialing to voice dialing. This preference was reversed after actual experience with voice dialing. People rapidly lost sight of the fact that human operators were in any way involved in their voice dialing. At the same time, there was evidence that they did not develop feelings of strangeness in talking to a machine. Stutterers had much less difficulty in calling numbers to a machine than they do in calling numbers to a telephone operator—this finding is perhaps not too surprising if one recalls that stuttering is largely a social phenomenon.

The range of telephone preference problems which have been studied by simulation methods is surprisingly extensive. In each case preference design requirements could be predicted for the devices proposed without the devices having to be built first. In some cases it was not even clear whether a device was technically feasible. Through simulation, insight was obtained into such problems as: the characteristics of audio warning signals which might be softer and pleasanter sounding that the telephone bell and still be as attention-arresting; the limits on the amount of time-multiplex circuit sharing by one particular method that would be detectable or acceptable; the ideal weight for a particular device that must be lifted in a particular way; the relative advantages of all-digit and combined letter-digit telephone numbers; the minimum transmission requirements for satisfactory television pictures.

Savings in time, effort and equipment by the use of simulation in preference testing have been rather impressive.

§ 2. Preference Principles

Among principles that we feel are fundamental to preference study and seem to be relatively well established are:

1. *Preference opinion without actual experience is unreliable.* Users must try out new devices or systems under normal real life conditions to find out what their preferences really are. Armchair experts also make mistakes in trying to forecast preferences on the basis of imagined experience.

2. *Initial preference opinions based on brief experience may be reversed by subsequent experience.* Experience with a new device should be extensive enough to overcome the user's preconceived biases and to permit him opportunity to evaluate all its important properties.

3. *Through simulation this experience can often be supplied to industrial personnel within the research organization.* Design information acquired from such experience materially increases the probability of a successful field trial of the device after it is finally built.

4. *Well planned simulation within the research organization should duplicate as closely as possible the field situation.* This includes: (i) users with a real need for the device—people cannot artificially generate or imagine needs; (ii) appropriate environmental conditions; (iii) a device or system which has precisely the properties of the ultimate device as far as the user's experience is concerned—users should not be required to ignore certain properties in the experimental device which would not be present in the final device, nor should they have to imagine any properties which the experimental device lacks but which would be present in the final device.

5. *In the simulation, users should be allowed to use the device as they want to use it.* To help achieve this, there should be minimum contact between user and experimenter; the user should be made to forget he is participating in an experiment.

Other possible principles which are still being evaluated include:

(*a*) Sudden changes in a device which produce unfavourable preference reaction may be unnoticed if made gradually in a series of small steps.

(*b*) Preference for a new device is more rapidly evaluated if the user alternates between his current device and the new one at suitable intervals, than if he uses the new device constantly.

(*c*) The user is not conscious of some of the properties of the device which affect his preference. The importance of such properties emerges only when they are changed.

(*d*) Unless the user's experience is fresh in his mind, design information based on his preference opinion may still be unreliable.

(*e*) The user's preference for a new device may be influenced by a knowledge of the reaction of other users. Such a suggestion may not be differentiated in the user's mind from his own actual experience with the device.

With growing complexity of technology, the problem of making machines that enable men to do more with less effort, is becoming more and more acute. The need for and use of user preference tests by engineers is growing rapidly. However, the engineer is concerned primarily with answers to his problems. He is not inclined to take time out to improve test methods. Accordingly the sharpening of preference testing tools, and techniques is lagging the demands for use. The opportunities for improvement of these tools and techniques seem ample and challenging, and possible returns appear to be substantial. The need for improvement is certainly not temporary : it will continue as long as technical advance continues.

Quelques points principaux de la méthode de déterminer les préférences des usagers pour de nouveaux dispositifs techniques sont illustrés au moyen d'exemples obtenus pendant une investigation parmi les usagers de téléphone.

Einige Hauptpunkte des Verfahrens zur Bestimmung der Bevorzugung neuer technischer Vorrichtungen seitens der Gebraucher werden anhand der während der Telefongebraucheruntersuchung erhaltenen Beispiele veranschaulicht.

FACTORS IN FATIGUE AND STRESS IN THE OPERATION OF HIGH-SPEED DIESEL PASSENGER RAILWAY CARS WITH ONLY ONE DRIVER PRESENT*

By Robert S. Schwab
Harvard Medical School, Boston

A case study is described of an elderly railroad engineer who made a number of errors in driving diesel trains. The recommendations made to the railroad company with a view to avoiding repetition of these incidents are listed.

In the course of our studies in the past years of problems of fatigue in human patients, we were asked by a railroad to study an elderly railroad engineer, age 74, who had on several occasions forgotten to stop his train at certain stations, and had had one or two minor accidents. A careful examination of this individual revealed normal electroencephalographic responses, motor reaction time, and, in general, excellent physical health considering his age. The problem of this particular man was that he was in charge of a single car train carrying passengers and mail over a distance of 200 miles. The arrangements for the operation of these single car trains is such that the railroad does not consider it necessary to have a second man in the operating cab. The engineer, therefore, is alone in this compartment during the entire trip which runs, including the approach to the terminus and leaving the destination station, approximately 6 hours. As is ordinarily arranged in railroading, the man makes a daylight trip in one direction and returns at night on another similar unit. We, therefore, requested permission to accompany him on his trip in the high-speed diesel single car. This trip involved a 200-mile run, with speeds at times over 70 miles an hour. We found that there were a number of distracting influences that might well produce early fatigue, with a tendency towards forgetfulness under different situations of stress.

§ 1. General Considerations

For nearly 100 years the second man in the cab of a locomotive in the United States has been called the fireman. In the days of steam locomotives his job was to keep the steam pressure up by shovelling coal. In between this task he would sit opposite the locomotive engineer and assist him with the identification of signals, train speeds and other problems, connected with the driving of the engine. Tradition and custom have developed the habit for the fireman when he was not throwing coal on the fire to call out the signals to the engineer across the cab who would repeat them. It is obvious that this system carried two advantages : (1) It kept the engineer in an alert awake state through an auditory stimulation and it confirmed the presence of any unusual signal warnings or obstacles in the track by having a second man watching. (2) There has also developed in railroading in the United States a tradition that the younger, vigorous man, going into locomotive operation would begin the first 10 years or so as a fireman, learning the various techniques and becoming familiar with every detail of the right of way, and assisting the regular engineer

* This work was supported by Office of Naval Research Contract with Harvard University. N.5 ORI–76 VIII NR 114–131.

in every possible way. Without planning it this way, the inevitable diminution of visual acuity, dark adaptation, colour vision, etc. that begins after 50 in ordinary people, is thoroughly balanced by the presence of a younger man in the cab watching out of the window.

As steam locomotives have been replaced in this country by the diesel, the word 'fireman' has become an anachronism and an absurdity but it is retained because of the traditions and habits of railroading. This has caused a certain amount of public distrust for the presence of a man called a fireman who does no firing as a possible cause for increased fares. In diesel engines which are now becoming the usual type in the United States, the second man in the cab would be much better called co-engineer or assistant engineer rather than fireman.

Furthermore, as the mechanical and operational facilities in diesel trains increased, single cars, running as the one mentioned above, began to be operated with only one man in the cab. Another tradition in railroading in the United States is that seniority of the engineer, i.e. age and the number of years that he has been with the railroad, entitles him to the fastest and best trains by a complicated system that need not be discussed here. This means that the oldest individual might well be in charge of the fastest train, and if this train happens to be a diesel operated car, a man in his seventies might be running such a train, in the night, alone. With the absence of the fireman in the cab, it is obvious that the elderly engineer, with his inevitable loss of visual powers, a tendency to have a slower reaction time, and affected by fatigue and stresses more easily than a younger individual, would be alone in the cab of such trains. He would lose the compensating presence of a younger man's vision and also the alerting effect of conversation and signal repeats. He would be very conscious of his responsibility and anxious to maintain his previous unblemished record in the railroad. He might well be disturbed by a great number of anxious moments.

At the time of this study there was no retirement in some railroads because of age. The only factors were physical disease, gross visual impairment or a request for retirement by the engineer himself. In some railroads the youngest engineer in charge of a locomotive or train was 49 years old, and the oldest was 81 years—the operator of a switch engine. The average age of several hundred engineers was 62 years. Retirement because of age has been adopted by some railroads at 70, and a few at 65.

Therefore, it seemed particularly interesting in this study of fatigue and stress to accompany this man on his trip and see what the problem was first-hand. Obviously the situation cannot be a true inspection because the trip involved the necessity of the presence of a guide, i.e. a district supervisor, and the engineer knew that two observers were present. The plan was to make the morning trip, and return the night trip. The return engineer would be a different individual but the problem would be the same. Since the day in question was in October, and a fair one, opportunities were provided to take still and motion pictures in colour, and motion pictures were made in black and white on the return trip.

The first source of stress that this observer noted was the fact that the bicycle type seat on which the engineer sat was not adjustable to his height. This was a matter that could be easily changed and in the recommendations at

the end of this paper was one that was carried out. The second factor, which was described as a safety factor, was the presence of the so-called ' dead man's pedal '. When the engineer is seated and starts the train it is necessary for him to press down on this metal pedal on the floor with his right foot and keep this pedal depressed until he brings the train to a stop. In the study of muscular fatigue it is well known that continuous contraction of muscle produces fatigue earlier than alternative contraction of muscles. Continual contraction of a muscle produces interference with the normal blood circulating through the muscles and this causes cramps, pain and, sooner or later, makes it necessary to partially release the muscle. In the case of foot pressure against a pedal it is possible by rotating the foot from side to side to release some of the continued contraction that causes disagreeable symptoms. However, this makes the contact with the pedal somewhat unstable and produces, in the mind of the operator, a certain amount of concern and anxiety lest his foot slip off the pedal during this kind of movement and rotation. If his foot comes off the pedal in such automatic types of brake control, emergency air will be put on, stopping the train suddenly. For operation where the intervals between stations are under 10 minutes, such as on subways, etc., it is not difficult to maintain efficient continuous pressure for this period of time, but in the case of the single unit trains the interval of time between stops may be as long as 50 to 60 minutes. In the case of this trip there was one uninterrupted run of 55 minutes. It is to be pointed out further that in elderly subjects the vascular supply to the plantar flexors of the foot in the gastrocnemius muscle may be sclerotic and, therefore, more sensitive to continuous pressure, interfering with normal circulation. Such individuals feel the cold more keenly in their feet than younger ones and in winter this continual pressure in the presence of a cold floor, which is inevitable in cold winter weather, makes the problem increasingly more complicated. In the case of the car studied by this observer the pressure exerted on the pedal to depress it was 7 pounds.

Since the escort with me was a divisional superintendent he began calling out the signals as the train went along and the engineer, seated on his right, then repeated them out loud. We understand that this is the usual technique in locomotives and cabs where there are two drivers present. It is very obvious that this kind of double checking using auditory communication between the two men has a strong alerting effect to keep awake and watching what is going on. It is far more specific in its alerting effect than ordinary conversation about outside subjects which would have a diverting effect.

Again, comparing single operation to the city rapid transit—elevated or subway trains, the time between stations is so short it is not necessary to depend on alerting signals of this type. In these single operated trains, however, where the time intervals may run up to one hour between stations, it seems exceedingly unfortunate that this alerting effect of intercommunication between two men is absent when there is only one man present. In situations where fatigue and stress are present, and where auditory sounds are absent, it is very easy in the presence of a straight, smooth track, for the operator to fall asleep or become drowsy. Unlike automobiles or buses, this could occur without disastrous effect because the train would continue at high speed along the rails, guided as it were, and not run off the road as is the case with an automobile or bus. Furthermore, in intercity buses where a single driver is in

charge, it is usual for this driver to be in the same compartment as some of the passengers. Here there are a number of alerting auditory effects which might prove useful in addition to the strong knowledge that falling asleep will cause the bus to run off the road.

Since the railroads, in general, are laid with some rather sharp curves in places, it is customary to indicate along the sides of the roadbed the speed limits for each particular section. These are painted on wooden signs usually, and adequate in size to be seen as the train approaches. The amount of time, however, for this number to be observed from its first readable appearance until it is passed the range of the operator's eye is only a second or two, at high speeds. This means that if the single operator should be watching a block signal on the opposite track or an approaching train, or other object, he might easily miss the speed limit sign. Again the presence of two operators—one more alert and younger—would make this less likely in this situation.

During daylight operation there are some sudden alterations in the light intensity from shadows of buildings, trees and embankments that occur over the right of way which elderly individuals might find interfere seriously with perception of possible objects in front of a train. This would not be a problem in the case of younger men under fifty, and would be minimized by two observers.

The usual, if somewhat primitive, arrangements in the old steam locomotive for relieving the bladder during the trip was to utilize the coal pile while one of the operators was in charge of the locomotive. No provisions were made in the steam locomotive for crew toilets. In the large diesel locomotives separate toilet accommodations are available in the engine, and one of the operators can temporarily leave the cab even though the train is running at full speed. In the single operated cars there are no provisions for relieving the bladder of the operator. It is possible, of course, for the operator to lock the cab at a station and proceed to the vestibule of the train and use the lavatory, but tradition and regulations forbid the flushing of the lavatory in the station which would be embarrassing to the operator. He could lock the cab and use the accommodations in the station where he stopped, but this would involve delaying the train a few minutes and would not meet with general approval. As a result of these difficulties it is usual for the operator of these trains on such runs to postpone relieving his bladder until the end of the trip. Obviously this causes discomfort and a certain amount of anxiety and stress. The custom of drinking coffee from time to time from a thermos flask, plus the obvious limits of elderly persons so that frequency and urgency are not unusual, complicate the matter further. There are all sorts of methods that could be used such as disposable cardboard cartons which could be used as urinals, or the installation of a flushable funnel drain in the cab which could solve the problem easily.

§ 2. Return Trip at Night

On the return trip of this same unit the problems became more complicated than during the daylight operation. No attempt was made to preserve dark adaptation during the trip back at night. At one point on the return trip the driver engineer commented that he was not certain as to whether he should stop at a certain station or not, the day being Saturday. Therefore, he turned on the white overhead lamp in the cab, glanced at his time-table, verified the

fact that he was not going to stop, then turned the light off. This observer started his stop watch to see how long it would take before dark adaptation returned to him and estimated that the rails were visible in some clarity after 2 minutes. This observer was 14 years younger in age at the time of this trip than the driver present so one could only guess that it was sometime longer for him to obtain the same degree of visual acuity, since it is well known that dark adaptation is a direct function of age. Since the train was proceeding at approximately 60 miles an hour, it covered 2 miles or more with a relatively blind operator.

Further complications involving dark adaptation occur when a train coming in the opposite direction passes. The bright headlight of the approaching train first showed in the cab of the train and dark adaptation was again destroyed for both the engineer and this observer. As the train approached, the headlight on the opposite train was extinguished. A few seconds later a dim light was put on. The same procedure occurred in our cab. After the trains had passed the bright light was again put on. It is quite obvious that this procedure could be eliminated as a source of dark adaptation interference by simply polarizing the operating front window of the unit and using a 90 degree angle glass in the headlight of all locomotives and diesel units. Such a procedure is very impractical with automobiles or buses due to the impossibility of getting everybody in line at the same time but with the railroad the procedure could be done over a week-end, for example, and there would then be no blinding effect at all. It certainly seems out of line with modern electrical switching that a single operated switch was not installed to dim the lights with one movement.

Since the glass cab has glass on three sides, and these glass panels are perpendicular, there is a tremendous amount of reflected glare from every light that the train passes. This intermittent glare interferes according to the brightness on the dark adapted eyes of the operater. Protective curtains could easily be arranged to reduce this particularly during night operation through populous areas.

Another source of interference with dark adaptation lies in the fact that the air pressure gauges are illuminated with white lights against black dials with black marks. The type of dial used in airplanes, ships and automobiles at night, where the illumination is red or violet, would take care of this difficulty.

This observer made the trip in clear excellent weather. One can only add by imagination the difficulties, stresses and interference with vision, and particularly dark adaptation when the ground is covered with snow or during severe snow storms or when ice, mist, fog or other hazards are present.

Most American railroads, even though the right of way is owned by the railroad, intersect highways, first, second and third class roads, private roads with level crossings. Many of these are guarded by gates or automatic warning signals but approximately 50 per cent are not. This observer counted 70 unwatched, unguarded crossings of this type during the first half of the trip in 100 miles. It is not unusual to read in the newspaper that an automobile was destroyed by a train at a grade crossing. Neglecting the side of the automobile owner and focusing attention only on the railroad and the operator's angle, these light-weight aluminum cars introduce other problems that were not present when the train was headed by a heavy iron steam engine. In those

older days, collision with a passenger vehicle was no physical or structural threat to the heavy locomotive, or to its personnel. With the present day light equipment, however, and with the operator at the very front of the train, his life may be in danger in a collision, particularly with something like a truck. This means that every unguarded, unwatched crossing presents a source of anxiety and stress as it is approached. It is obvious that this problem is one that will not be solved easily. The presence of two operators, one of whom has youthful or mid-adult vision, increases the chance of preventing such accidents by seeing the vehicle in time.

§ 3. Conclusions

In one study of a high speed diesel rail car with but one driver present in the cab, a number of factors which increased both fatigue and stress were noted. These were :

(1) There was no practical way for the engineer to relieve his bladder during the $5\frac{1}{2}$ hours that he was on this run.

(2) Alone in the cab of this high-speed train, there were no alerting auditory stimuli that ordinarily occur when a co-engineer is present. The continual calling of signals and speed zones which the engineer repeats aloud preserves alertness and attention.

(3) The presence of a so-called 'dead man's pedal', which required positive pressure with the foot against a $7\frac{1}{2}$ pound spring produces in a normal person intense muscular fatigue after a 10 minute interval. In this particular run the longest time which the pedal had to be kept pressed down was 55 minutes. There was no way to shift this pedal to the other foot or relieve it by hand control.

(4) The bicycle-type seat on which the engineer sat was not adjustable, and tended, if the engineer should faint, to throw him forward into a slumped position with his full weight on the safety pedal.

(5) In addition to close inspection of the track ahead, the engineer had to watch the speed zone safety limits from signs on the side of the track to his right, as well as an internal set of block signal lights in the cab on his left. Above his visual field and to the right were two air pressure gauges that he had to follow. These three distractions in his peripheral field made attention directly ahead more difficult.

(6) On the return trip, which was at night, there were a large number of disagreeable reflections from passing lights which entered the cab from three sides. There was no way for the engineer to look at his orders and schedule without turning on the overhead bright light and ruining his dark adaptation, partial restoration of which may take 2 minutes in a man over sixty. During this period he is nearly blind.

(7) Oncoming trains that were passed, and this unit too, dimmed their lights by switching off the high beam and then putting on the low beam. This resulted always in a brief period of several seconds of no headlight at all or another type of blindness that is very distressing.

It was felt, and so recommended to the railroad, that in view of the stresses that produced fatigue because of the seven factors mentioned above, it was not wise to have elderly men, even though they were up to the usual physical standards of their age, in charge of such high-speed trains *alone*. It was recommended that engineers be retired after the age of 65, or in high-speed trips that last more than an hour, a co-engineer be present in the cab at all times. It would seem also that a number of electronic, mechanical, and optical aids could be worked out in the future that would make the responsibility of the driver of such high-speed trains less dependent on his own sensory systems. These would be :

(*a*) Anti-glare curtains for night use.

(*b*) Automatic dimming of the headlights of approaching trains.

(*c*) The printing of orders and schedules in large letters, on a transparent surface so that they could be examined by means of a red light without jeopardizing dark adaptation.

(*d*) Some method of automatic train control so that when a unit exceeded the speed limit for the section in which it was running, an alarm bell would sound in the cab.

(*e*) A more efficient and less fatiguing type of safety ' dead man's ' air brake control pedal.

The problem of eliminating the stress of a full bladder in an elderly person on such a run as described could be solved in so many ways that no specific recommendation was made. When two engineers are present, this problem would not exist.

On décrit l'histoire d'un mécanicien âgé, qui avait commis un nombre d'erreurs en conduisant des trains à traction Diesel. On énumère les recommandations proposées a la société des chemins de fer afin d'éviter la répétition des accidents.

Die Geschichte eines älteren Maschinisten, welcher mehre re Fehler bei der Führung von Dieselzügen gemacht hatte, wird geschildert. Die Empfehlungen, welche der Eisenbahngesellschaft zwecks Vermeidung der Unfallswiederholung mitgeteilt wurden, werden aufgezeichnet.

SUMMARIES OF PAPERS PUBLISHED ELSEWHERE

Authors of papers of ergonomic interest which have been published in other journals or which are available as privately circulated reports are invited to submit summaries for publication in this Journal. They may be sent to any member of the Editorial Board and should be accompanied by a copy of the full paper which will be returned to the author on request.

Schut, J. H. (1957), Handtransport van kisten, *Tijdschrift voor Efficiency en Documentatie*, **27,** 19–21.

Four methods of material handling were compared in an experimental situation. The following criteria were used : time study, energy expenditure and pulse rate. Four experienced dock-workers handled cases of 65 kg weight (dimensions $15 \times 15 \times 21$ inches) in different ways. Calculations were carried out as to the mechanical work and compared with the physiological reactions.

Statistical analysis of the data obtained shows that handling these cases by turning them in balance on the angular points, is a significantly better method than tilting over from side to side.

There was a better agreement between energy expenditure and mechanical work than between pulse frequency and mechanical work. The desired recovery time as a percentage of work time could be derived from the caloric expenditure.

Murrell, K. F. H. (1957), Data on human performance for engineering designers. *Engineering*, *Vol.* 184. *Pp.* 194–198. *Aug.* 16, 1957.

These articles are designed to set out results of research in the ergonomics field in a form in which they can be used for ready reference by engineering designers.

The first article deals with designing equipment for human use, in particular with the problems raised by control panels : with body structure and movement including a table of the limits of joint movement : with body measurement giving a table of anthropometric data for men and women : with seating in which the principles of good seating are illustrated with photographs.

Pp. 247–249. *Aug.* 23, 1957. In this article the type of display to be used for different purposes is discussed. The factors to be considered in laying out the face of a dial are given, including the scale marks, numerals, pointers, reading distance and colour. Indicators, and auditory and tactual displays are also dealt with.

Pp. 308–310. *Sept.* 6, 1957. Controls are classified and data relating to each are given, including sizes, torques or forces which can be developed and position in relation to the operator. The relationship between controls and associated displays is discussed and the control to choose for various purposes is given.

Pp. 344–347. *Sept.* 13, 1957. The methods of Belding and Hatch in assessing industrial heat strain and the use of aluminium foil for screening are

described. The results of research on the damaging effects of noise, noise and communication and noise and efficiency are summarized. Some methods of reducing industrial noise are recommended.

Pp. 438–440. *Oct.* 4, 1957. The factors which will influence the amount of light on a job are discussed and a nomograph is given for calculating the brightness required when the contrast and size of the task are known. Glare and colour are also dealt with.

The whole series is published by " Engineering " as a 32-page booklet.

FORTHCOMING ARTICLES

Among papers already accepted for publication in subsequent issues of this Journal are the following :—

" Research on Human Factors in Road Transport ",
by G. Grime, Road Research Laboratory.

" Simplifying the Operator's Task as a Controller ",
by A. W. Bailey, U.S. Naval Research Laboratory.

" The Strength of the Lifting Action in Man ",
by R. J. Whitney, Medical Research Council, Unit for Research on Climate and Working Efficiency.

" Headlight Design ",
by R. L. Moore, Road Research Laboratory.

" Measurements of Visibility from the Driving Seat of Motor Vehicles ",
by R. A. C. Fosberry, The Motor Industry Research Association.

" Training Older Operatives ",
by Eunice Belbin, Medical Research Council.

" Physiological methods for estimating the physical working capacity in workers, especially of the older age groups ",
by Irma Rhyming, Gymnastic Institute, Stockholm.

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Psychological Laboratory, Downing Place, Cambridge.

PROCEEDINGS

A Meeting was held jointly with the British Occupational Hygiene Society in the London School of Hygiene on 28 June, 1957, at which the following papers were presented :—

(1) " A Brief Study of Accidents in the Steel Industry ", by G. G. Mathew, Richard Thomas and Baldwins Limited.

The paper is descriptive and does not attempt to draw any important conclusions and is drawn from experience of the Steel Industry with particular reference to steel, sheet and tinplate works. An attempt will be made to compare the patterns of accidents in old and new plants. Studies of accidents are usually statistical but unless the means of collecting the information is standardized these statistics are not comparable. It is maintained that the study of accidents should be clinical and that each accident should be approached in the same way as a patient requiring diagnosis. As in diagnosis the history of the accident is of prime importance ; this includes the circumstances leading up to the accident and the circumstances applying at the time of the accident, both from the injured person's point of view and the environmental point of view. Two or three illustrative cases of accidents are given.

(2) " Health in the Royal Navy and Standards of Environmental Warmth ", by F. E. Smith, Medical Research Council.

In 1944, acting on the advice of the Medical Research Council, the Naval Staff provisionally accepted certain standards of warmth which should not be exceeded in warships if the men were to remain efficient and healthy. Work was then begun to test the validity of these standards and the results have shown that from the viewpoint of the mens' efficiency they are acceptable. The object of this paper is to describe how the effect of hot living conditions on the mens' health has been examined and to show how minor sickness is affected when these recommended standards are exceeded.

The investigation was begun in 1945 by instituting a new form of sickness return to H.M. Ships and the first review of these in 1948 showed how useful the incidence of minor sickness could be in revealing the effect of hot climates on the men's health. The return was therefore continued with an amendment which required the upper deck air temperature to be included.

The next examination, in 1952, showed the value of the temperature measurements—a steady increase in minor sickness as the weather became hotter was seen. The trend was such that when the upper deck air temperature at noon exceeded 80°F a marked increase was noted which was even more pronounced when the temperature rose above 90°F. This result was not entirely conclusive, however, because the trend could only be shown by grouping the returns from all classes of ship and from all stations.

The analysis of the returns covering four years, which is discussed here, indicates that the trend is fairly general in all classes of ship when serving on most foreign stations. It has also been possible to establish the trend more precisely, because of the larger numbers of returns, and the results have also been used to show how minor sickness generally, and skin disease particularly, increase significantly when the standards are exceeded in the living spaces. Thus the recommended standards of environmental warmth also appear to be valid from the viewpoint of the men's health.

The value of the more recent policy of air-conditioning some warships to prevent these standards being exceeded on very hot stations is evident from the results. It has been possible to assess the considerable reduction in minor sickness, particularly skin disease, in sloops serving in the Persian Gulf after air-conditioning has been installed.

(3) "The Effect of Prolonged Exposure to Intense Noise on the Hearing of a Group of Industrial Workers", by S. Laner, British Iron and Steel Research Association, London.
On the initiative of Dr. G. F. Keatinge, Medical Officer of the Butterley Co., Ltd., Ripley, measurements of noise were taken in three assembly shops; these yielded readings sufficiently high to indicate that prolonged exposure without protection might well lead to hearing loss. Subsequent frequency analysis showed that the noises reached peak intensity at frequencies between 1000–2000 c.p.s. A hearing loss chart devised by Fowler and Sabine for the American Medical Association was used to assess the binaural hearing loss of some 70 workers employed in the noisy shops at Butterleys and exposed continuously for periods from under 1 year to 7 years. On the basis of a statistical analysis a tentative hypothesis was formulated on the relationship between length of exposure and hearing loss.

(4) "The Prevention of Accidents in Industry," by R. W. Newby, H.M. Inspector of Factories, Wolverhampton.

(5) "Accident Control Charts," by D. W. Widginton, Safety in Mines Research Establishment.

(6) "Hazards Associated with the Newer Systemic Insecticides," by G. F. Carter, Imperial Chemical Industries.

Preliminary notice is given of the Symposium to be held at the University of Bristol from 13 April to 16 April, 1958, on "The Problems of Training: physiological and psychological aspects of training for muscular work and the acquisition of skills".

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The Philosophical Magazine

First Published in 1798

Contents of November, 1957

Price per part £1 5s. plus postage
Price per annum £13 10s. post free, payable in advance

Printed and Published by

TAYLOR & FRANCIS LTD

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ERGONOMICS

Volume 1 November 1957 Number 1

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